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2400-VOLT RAILWAY ELECTRIFICATION

BY H. M. HOBART

The employment of electricity as the motive power for sections of railway on which a dense service is maintained has long since been demonstrated to be desirable from many standpoints. For such undertakings it is a point of relatively minor consequence whether the railway provides its own power house or purchases its electricity from independent undertakings. In the former case the capital outlay involved in carrying through the electrification is increased, but the total of the annual capital and operating costs is rarely much affected by the choice between these two plans. It requires a careful consideration of each specific case to determine which of the two policies will lead to the most economical result. The difference will usually be so slight as to involve no wide-reaching consequences.

Nevertheless, on the broad principle that specialization and concentration are usually in the interests of true economy, the general recommendation can be made that in cases where no obvious considerable advantage accrues to the railway from owning the electricity-generating plant, and where satisfactory terms can be obtained from an independent electricity-supply company, it is on the whole desirable to purchase the electricity, leaving the railway company to concentrate the abilities of its engineers on the immediate problems of railway operation. Usually the independent electricity-supply company should be able to provide the electricity at an attractive price for the reason that the annual consumption will usually be quite an addition to its lighting and miscellaneous power load and for the further and important reason that the time-distribution of the railway load will usually be such as slightly to improve the total load factor at the generating station. These points have been emphasized

in a paper entitled *The Relation of Central Station Generatio to Railway Electrification*, presented by Mr. Samuel Insull befor the American Institute of Electrical Engineers on April 5, 1912

There are, however, other classes of railway traffic where it woulc be a great and often a hopeless handicap to the project were the railway to provide its own power house for the supply of electricity. These classes of traffic are, nevertheless, of great importance. They consist in relatively sparse services of high-powered trains. When the load represented by such traffic can be supplied from the same generating stations which supply power for a dense urban and suburban service, its sparse character presents no special disadvantage. But for other sections where the traffic consists chiefly or exclusively of only a few (say eight or ten) high-powered trains passing daily in each direction, a power station built and operated for the exclusive purposes of this sparse traffic, could only provide the required electricity at a cost very much in excess of the price at which it could be purchased from stations already supplying a large quantity of electricity for lighting and power purposes.

It is only during the last few years that the growth of the electricity generating and supply business has increased to the enormous extent to justify the statement that it already forms a fair approach to a complete network throughout most of the moderately-settled sections of this country. It has thus come about that in estimating upon the electrification of many important sections of railway where the traffic consists of relatively few high-powered trains per day, the estimates can be based upon the purchase of electricity from some large electricity-supply station to which the additional load will be so welcome with respect to the increase which it effects in the quantity of electricity to be manufactured annually, that, notwithstanding the irregular nature of the load, the electricity can be supplied to the railway at a very moderate price. In a later section of this paper, allusion will be made to further reasons contributing to this result.

Present Position

The upshot of this altered state of affairs is that propositions which, only a few years ago, must inevitably have been dismissed as not within the economic range for electrification may now be demonstrated to be highly attractive and from all standpoints commercially reasonable. By working out in this paper a few simple comparisons, attention will be drawn to the leading facts which must be taken into consideration in such estimates. No

attempt will be made to work out *detailed* quantitative estimates: on the contrary, the only quantitative data put forward in the paper will be of a kind to indicate tendencies and to draw attention to the general order of magnitude of the corresponding costs for steam and electric operation. The investigation will be confined exclusively to traffic of the nature indicated, namely, high-powered freight and express-passenger trains, as it is for this class of traffic that it has until recently been considered that steam locomotive methods possess inherent characteristics of an economic nature which could not be rivalled by alternatives in which electric locomotives are employed.

Let us first consider a case where it would naturally be claimed that the steam locomotive would be most strongly entrenched; namely, an express passenger service. It is not asserted that the results of the estimates which will be put forward are necessarily inconsistent with the above claim, but rather it is intended to point out that, even in so extreme an instance, there are attractive possibilities in the electric-locomotive alternative.

Express Passenger Service

An express locomotive hauling a passenger train on any one of our Eastern railways will in actual service burn at least 3.5 pounds of good coal per indicated horse power hour. As a representative train we may take for example a Pacific-type locomotive weighing, complete, 185 tons[1] and hauling 10 modern Pullman coaches constructed of steel and weighing 75 tons each. There is thus an aggregate weight of $10 \times 75 = 750$ tons behind the locomotive. Of the total locomotive weight of 185 tons, the tender accounts for no less than 70 tons. Even of the remaining 115 tons only 85 tons is carried on the three driving axles, or 57,000 pounds per axle. On the basis of a coefficient of adhesion of 0.20, the locomotive can exert a tractive effort of

$$0.20 \times 85 \times 2000 = 34{,}000 \text{ lb.}$$

before slipping the wheels. For the usual requirements of an express passenger service, this limit will rarely be approached. The total train weight amounts to

$$185 + 750 = 935 \text{ tons}$$

Typical of the service of such trains is the making of non-stop runs of, say, 100 miles in two hours. This corresponds to an

1. The 2000-lb. ton (= 0.9 metric ton) is employed throughout this paper.

average speed of 50 miles per hour. In the course of this 100-mile run, *maximum* speeds of over 60 miles per hour will be attained. The average tractive effort, taking into account the variations in speed, and assuming representative track conditions as regards curves, grades, and weight and condition of rail, for a train of this composition, will be roughly 9 lb. per ton.

The total tractive resistance will be

$$9 \times 185 + 9 \times 750 = 1670^* + 6750 = 8420 \text{ lb.}$$

On the basis of an efficiency of 85 per cent from the cylinders to the crank-pins, the power required, averaged over the journey, will be

$$\frac{50 \times 5280 \times 8420}{60 \times 33{,}000 \times 0.85} = 1320 \text{ i.h.p.}$$

On the basis of an average consumption of 3.5 lb. of coal per i.h.p-hr., there will be burned during the journey

$$2 \times 1320 \times 3.5 = 9240 \text{ lb. of coal}$$
$$\text{or } 4620 \text{ lb. per hour.}$$

This quantity is based on the use of coal of a calorific value of some 14,000 B.t.u. per pound. Since 1 h.p-hr. = 2545 B.t.u., we may express the calorific value of the coal as

$$\frac{14{,}000}{2545} = 5.50 \text{ h.p-hr. per lb.}$$

The energy in the coal burned on the journey amounts to

$$9240 \times 5.50 = 50{,}800 \text{ h.p-hr.}$$

The energy output from the cylinders is

$$2 \times 1320 = 2640 \text{ i.h.p-hr.}$$

Consequently the "journey" efficiency from the coal to the cylinders is

$$\frac{2640 \times 100}{50{,}800} = 5.20 \text{ per cent.}$$

It is highly improbable that this "journey" efficiency is ever exceeded in routine steam locomotive haulage.

* Throughout this paper the accuracy is limited to three significant figures.

In accordance with our assumption of 85 per cent for the efficiency from the cylinders to the crank-pins, we obtain for the "journey" efficiency, from the coal to the crank pins,

$$5.20 \times 0.85 = 4.41 \text{ per cent}$$

But a considerable portion of the energy delivered at the crank-pins is consumed in propelling the locomotive itself. Of the total tractive effort of 8420 lb., no less than 1670 lb. is required for the locomotive, and only 6750 lb. remains available for propelling the train behind the drawbar. Consequently the "journey" efficiency from the coal to the drawbar is only

$$\frac{6750}{8420} \times 4.41 = 3.53 \text{ per cent}$$

It must furthermore be pointed out that coal is burned wastefully in firing up before the journey and also for a considerable time after the journey.

For the case in hand a fair value to assign to the aggregate of these two components is 3000 lb.

There must consequently be debited to the 100-mile journey a gross coal consumption of

$$9240 + 3000 = 12{,}240 \text{ lb.}$$

This reduces the net efficiency from the coal to the drawbar to

$$\frac{9240}{12{,}240} \times 3.53 = 2.65 \text{ per cent}$$

Thus per drawbar h.p. hr. we require to burn

$$\frac{5.20}{2.65} \times 3.5 = 6.86 \text{ lb. of coal.}$$

Now let us consider the hypothetical case of an *electric* locomotive hauling these 10 Pullman coaches over the same distance in the same time.

In order to provide equal margins as regards starting, accelerating, ascending grades, and operation at high speeds, we must, so far as relates to the provision of the same drawbar pull, arrange for the same weight on drivers per ton total weight of train. The steam locomotive had a weight of 85 tons on drivers,

and the complete train weighed 935 tons. If the electric locomotive were built with the entire weight on drivers, then if by W we designate its weight, and remembering that the weight of the 10 Pullman coaches is 750 tons, we should have the relation

$$W : 85 = (W + 750) : 935$$
$$\text{Whence } W = 75 \text{ tons}$$

While we thus see that a 75-ton electric locomotive provides the required capacity, it is necessary, in the interests of ensuring smooth running at high speeds, to provide guiding trucks at each end.[2]

Fifteen tons is an approximate figure for the weight of each of these guiding trucks. The correct method of arriving at W, the weight of the locomotive, when, as in the present instance, the speed is such as to require two 15-ton guiding trucks, is as follows:

$$(W - 30) : 85 = (W + 750) : 935$$
$$\text{Whence } W = 108 \text{ tons}$$

The weight on drivers is

$$108 - 30 = 78 \text{ tons}$$

As now modified, we may take the complete weight of the electric locomotive as 108 tons, of which 78 tons is on drivers. For the electric equivalent of our typical steam train we thus have a train with a total weight of

$$108 + 750 = 858 \text{ tons}$$

as compared with the weight of

$$185 + 750 = 935 \text{ tons}$$

for the steam train.

For the electrically propelled train the average tractive effort for the journey is

$$9 \times 108 + 9 \times 750 = 972 + 6750 = 7722 \text{ lb.}$$

2. For locomotives whose *maximum* speed is less than 45 miles per hour, no wheels in addition to the drivers need be provided. The great advantage of the electric locomotive of providing double-end operation, is, for high speeds, only secured at the cost of providing *two* bogie trucks, one at each end. One of the bogie trucks places it on a par with the steam locomotive, in respect to single-end operation; the other truck endows it with the great advantage of double-end operation.

The average power required at the rims of the drivers works out at

$$\frac{50 \times 5280 \times 7722}{60 \times 33{,}000} = 1030 \text{ h.p.}$$

The energy expended at the rims of the drivers during the 100-mile journey is

$$2 \times 1030 = 2060 \text{ h.p-hr.}$$

It will now be shown that the over-all efficiency from the coal pile in the power house, to the rims of the drivers, is, for practically any well designed and commercially sound railway scheme purchasing its electricity from large, independent electricity-supply stations, of the order of 6.0 to 6.5 per cent.

As a representative value for the annual over-all efficiency of a large modern, steam-driven electricity-supply station (*i.e.*, the efficiency from the coal pile to the outgoing cables), we may take 11 per cent.[3]

Over-all Efficiency

When designed with due consideration for the economic balance between capital and operating costs, the annual over-all efficiency of the transmission line will usually be of the order of 95 per cent. For a dense service, the annual over-all efficiency of the substations will be at least 89 per cent, and even for a sparse service it will usually be above 78 per cent. The efficiency from the substation to the trains will be of the order of at least 93 per cent for both classes of service. The annual over-all efficiency of the train equipments will be of the order of 71 per cent

3. A few years ago 9 per cent would have been considered a high figure for the over-all efficiency of large generating stations, and efficiencies of only 6 to 8 per cent were the rule. The increase over these figures constitutes, in itself, considerable reason for reconsidering railway electrification limitations. One kw-hr. = 3411 B.t.u. A generating station has an over-all efficiency of 11 per cent when, taken over an entire year, the B.t.u. in the coal consumed per kw-hr. of output from the station, average (3411/0.11 =) 31,000. On the basis of coal of a calorific value of 14,000 B.t.u. per pound, an over-all efficiency of 11 per cent is obtained when the coal consumption for the entire year is (31,000/14,000 =) 2.21 lb. per kw-hr. of output from the power house. Over-all efficiencies of from 10 to 11 per cent were obtained as early as 1905 at generating stations in Stockholm, Berlin, Vienna. (See pages 29, 34 and 47 of the author's "Heavy Electrical Engineering," Van Nostrand), and at the Interborough's 59th St. station in New York. (See page 3 of Vol. XXV, of Trans. A. I. E. E.). Annual over-all efficiencies of 11 per cent now are obtained in the more important Edison stations. At the Interborough's 59th St. station, the annual over-all efficiency is now over 12 per cent.

for a service of frequently stopping trains, and of the order of 87 per cent for a service of trains running long distances between stops. The annual over-all efficiency from coal pile to driving-wheels is thus

for dense service, $0.11 \times 0.95 \times 0.89 \times 0.93 \times 0.71 = 0.061$
" sparse " $0.11 \times 0.95 \times 0.78 \times 0.93 \times 0.87 = 0.066$

Thus for a service of trains making long runs between stops, a value of 6.5 per cent may be considered as representative of the order of magnitude of the annual over-all efficiency from the coal pile in the generating station to the rims of the driven wheels on the train.

Let us then, in the present instance, take the over-all efficiency from coal pile to drivers, as 6.5 per cent. Then the quantity of coal (of a calorific value of 14,000 B.t.u. per pound, or 5.5 h.p-hr. per pound), burned at the electricity-supply station, which should be debited to the 100-mile journey of our express passenger train amounts to

$$\frac{2060}{5.5 \times 0.065} = 5750 \text{ lb.}$$

This constitutes only

$$\frac{5750 \times 100}{12,240} = 47 \text{ per cent}$$

of the amount of coal which is required in the case where the same train of 10 Pullman coaches is hauled by a steam locomotive.

The quantity of coal in the two cases may be compared as follows:

122 lb. per train-mile for steam locomotive
58 " " " " electric "

Including the locomotives in the weights of the trains, these figures reduce to

$$\frac{122}{935} = 0.130 \text{ lb. per ton-mile for the steam train}$$

and

$$\frac{58}{858} = 0.068 \text{ " " " " " electric "}$$

But on the basis of coal consumption per ton-mile of *useful* load (*i.e.*, per ton-mile *behind the drawbar*) we have:

For the steam train, $\frac{122}{750} = 0.163$ lb. of coal per ton-mile

" " electric " $\frac{58}{750} = 0.077$ " " " " "

A non-stop express run has purposely been taken in making this comparison, since it represents the case where steam locomotive methods appear to best advantage in comparison with electric locomotive methods. Had occasional stops been assumed, the comparison, as far as relates to low fuel consumption, would have been still more favorable to the electric locomotive. There are the further considerations that, first, the cost of the coal delivered at the convenient site always with purpose selected for the generating station, is materially less than the cost of the same coal by the time it is loaded on the locomotive tenders; and second, a cheaper grade of coal can economically be employed in a generating station than on steam locomotives. Thus if the comparison were carried beyond the *quantity* of coal per train-mile and reduced to terms of the fuel *cost* per train-mile the result would, in most instances, be to increase the ratio of 1 (for the electric locomotive) to 2 (for the steam locomotive), to a ratio more of the order of 1 to 3.

Steam versus Electric Operation Costs

Electricity will certainly be employed to a gradually increasing extent for trains of the character we have considered, over sections of line where the requirements of other classes of traffic have been such as to justify the electrification of the line. Typical are cases where the bulk of the traffic consists in a dense service of suburban passenger trains making frequent stops and nevertheless maintaining a relatively high schedule speed. In several other instances, it has been the difficulties and dangers attending the operation of steam locomotives in long tunnels, which has occasioned the electrification of the railway. The point which it is desired to emphasize is that it has, as yet, *never been* in the first instance, a *consideration of the merits of electrical as compared with steam locomotive methods for the operation of express passenger trains*, which has led to electrification. Rather it has been in the face of a generally accepted (and heretofore entirely reasonable) opinion that for this class of service, steam locomotive haulage is economically much the more appropriate.

It is only gradually beginning to be recognized that even for a relatively sparse service of freight trains and express passenger trains, the economies in the direction of decreased fuel consumption, decreased outlay for maintenance and repairs of locomotives, elimination of firemen on locomotives, (and the substitution therefor of an assistant engineer to be available in the event of unforeseen incapacity on the part of the responsible engineer,) elimination of heavy tender, and (which will ultimately be found to be of specially great importance), increased annual mileage per locomotive, will in many instances amply justify the capital outlay involved in electrification. Caution must, however, be used, for there are at present many cases where the traffic is so sparse, the cost of electricity so considerable, and the outlay of such magnitude, (as compared to the sparse traffic), as to demonstrate steam locomotive methods to be distinctly appropriate and to constitute the economically correct system.

However, the trend of developments is strongly in the direction of extending the legitimate field for the electrification of railways. Practically all moderately settled sections of the United States are now covered with extensive electric transmission and distribution systems of great capacity. It is becoming increasingly customary to effect interconnecting arrangements between the various systems, and it appears that there will be a rapidly-increasing tendency toward providing what will, to all intents and purposes, constitute a few large networks. Steadily increasing loads and improved machinery, accompanied by scientific management, are continually leading to reductions in the prices at which electricity can be sold at a fair profit. Thus it is rapidly becoming increasingly more practicable for railways to purchase their electricity along the line of route, thereby limiting their own capital outlay to that associated with substations, feeders, contact conductors, and rolling stock. Usually the rolling stock will constitute the largest item in the capital outlay even when the service is far from dense.

Not only is there associated with the policy of purchasing the electricity the advantage of avoiding the capital outlay for electricity generating stations and for transmission lines, but there is the important consideration that the railway load is of such a character that when superposed on the present loads supplied by the undertakings, a price per kilowatt-hour can be accepted which will be lower than the cost at which the railway could make its own electricity. The railway company will usually find that

the most suitable arrangement consists in providing its own sub-stations and purchasing from a supply undertaking the electricity in the three-phase form in which it is delivered at the sub-stations.

2400-Volt System

To the railway the question of so designing its system as to secure the requisite conditions with a reasonable outlay for sub-stations and for the feeders and the contact-conductor system becomes one of much importance. For a relatively sparse service, the 2400-volt system bids fair to be adopted widely. We have seen that the average power required at the drivers of an electric locomotive hauling 10 Pullman coaches at an average speed of 50 miles per hour is some 1030 h.p. At constant speed, the efficiency of the electrical equipment on the train will be of the order of 90 per cent. The average input will thus be a matter of some 1150 h.p. But during acceleration and when ascending grades, the input will rise, say, to 1600 h.p. or ($1600 \times 0.746 =$) 1200 kw. At 2400 volts this requires collecting a current of

$$\frac{1,200,000}{2400} = 500 \text{ amperes}$$

This current can readily be collected by pantograph trolleys.[4] Moreover, currents of much greater magnitude than this may be transmitted many miles without exceeding a reasonable pressure drop and without requiring prohibitive outlay for positive and negative feeders. The more widely apart the substations are spaced, the higher (with a sparse service) will be the load factor, and the greater will be the rated capacity of each substation (and consequently the lower will be its capital cost per kilowatt of rated capacity) and, finally, the lower will be the wages outlay associated with the

4. For a given life of the contact roller, tests reveal the following relation between the speed of a pantograph trolley and the current which can be collected:

Speed in miles per hour	Current in amperes
10	1200
20	900
30	600
40	450
60	300

When estimating on two pantograph trolleys in parallel, it is well to consider their combined capacity as only 1.75 times that of a single trolley.

operation of the substations. For 2400-volt substations, the spacing will usually be from some 30 miles apart for a relatively sparse service of high-powered trains, down to some 15 miles apart with more frequent trains. With any approach to a dense service, 1500 volts or 1200 volts would amply suffice, the substation spacing ranging from 15 miles down to some five miles. From this point downward, we come within the order of things corresponding to a very dense urban and suburban traffic. In such cases, if the area is very extensive, as at Melbourne, a 1200- or 1500-volt system may appropriately be employed, but it will be more usual and satisfactory to employ some 600 to 750 volts for the exceedingly dense traffic requirements in, through and near a great city or the metropolitan district comprising two or more adjacent cities and their suburbs. It is not only possible but will often be eminently practical and desirable to combine the use of 600 or 750 volts in the near neighborhood of a great city, with the use of 1200 or 1500 volts for more remote sections where the traffic is more sparse, and the same rolling stock will be operated indifferently from either pressure.

The decision between the use of a third rail or an overhead contact-conductor is not in any sense an embarrassing one, but is readily settled in accordance with the circumstances of each case. Good use will often be made on the same system, of overhead contact-conductors on some sections and third rail on other sections, the rolling stock being readily equipped with contact appliances for both systems.

Returning to a consideration of the 2400-volt system, it may be said that pairs of 1200-volt motors in series will, so far as control methods are concerned, take the place of single motors. The most usual plan will consist in driving four axles of the locomotive from the four motors. But 1200 volts is by no means the limiting pressure for the commutator of a railway motor and it would be sound engineering to employ four 1800-volt motors connected in 3600-volt pairs on a four-axle locomotive operated from a 3600-volt contact conductor. Where the required performance of the locomotive would make it preferable to have six driven axles, the equipment could comprise six 1200-volt motors arranged in two groups, each group being made up of three motors connected in series and regarded as a single motor so far as relates to the series-parallel control features. The objections originally made that with two motors in series driving independent axles, there would be trouble if one set of wheels slipped and occasioned

most of the voltage to be concentrated on the motor coupled to these wheels, have, in practise, not been realized. In the improbable event that difficulties should arise from related reasons in future constructions, either resort could be had to employing connecting rods, or else two motors in series could drive the same axle by each having pinions engaging with the gear wheel or gear wheels on this axle. It may be as well here to point out that for the operation of trains making runs of several miles between stops, there is less justification for series-parallel control than has been the case with the frequently starting and stopping trains for which electrical operation has heretofore been regarded as especially appropriate.

Mountain-Grade Railways

A keen interest is at present being taken in the electrification of mountain-grade divisions of main-line railways in the Western states of this country. In several concrete instances, careful estimates have demonstrated that the operating economies which can be effected by superseding with electric locomotives the steam locomotives on such railways are enormous, and are indeed, of such amounts as to defray in a very few years the initial outlays for substations, for feeders and contact-conductors, and for electric locomotives.

A chief factor contributing to this result relates to the very low cost at which the large hydroelectric supply companies in the West can profitably sell electricity for operating synchronous motors in substations. A considerable proportion of the present load of these hydroelectric undertakings consists in induction motors. The large lagging component of the current consumed by induction motors involves capital and operating costs which are very much in excess of the corresponding costs of supplying equal amounts of energy at unity power factor. Synchronous motors may with advantage be so operated as to consume a current with a large leading component. It often pays an electricity-supply company to go to the expense of purchasing and installing large synchronous motors for the express and exclusive purpose of running them idle and with high excitation, simply to neutralize the lagging component of the current consumed by the induction motor load. If the electricity-supply companies can find customers who will take upon themselves the expense of purchasing such synchronous motors and who will so operate them from the electricity-supply companies' system as to neutral-

ize the undesirable lagging component, then they are spared the necessity of themselves incurring this capital outlay for improving the conditions on their system. Although the electricity-supply companies may not be able to satisfy themselves that they can equitably pay the railway companies for operating synchronous motors from their systems, nevertheless it will be seen that exceptionally low prices, satisfactory to both parties to the transaction, should readily be agreed upon. The equitable price in such a case should be arrived at on the basis of debiting the railway company with the value of the energy delivered to the substations and crediting the railway company with the value to the supply company of the leading current drawn from the system by the over-excitation of the synchronous motors in the substations.

The electricity-supply companies' traditional objection to a railway load of the sparse character associated with the operation of mountain-grade divisions, has, in the past, related to its very poor load factor. But when it is understood that these Western hydroelectric companies already have enormous loads connected to their systems, it will be seen that the fluctuations of a couple of thousand kilowatts, more or less, imposed by the intermittent operation of a few freight trains, is not a factor of consequence, especially since it does not affect the leading component of the current consumed by the synchronous motors.

Engineers have in the past usually erred in their ideas regarding the order of magnitude of a railway load. The present electricity-supply companies distributed about the country could often handle the load corresponding to relatively large railway undertakings without incurring the expense of any very considerable extensions of their generating and transmitting installations.

Let us illustrate this point by the case of the Butte, Anaconda and Pacific Railway, which is electrifying 90 miles of track with the 2400-volt system. The equipment comprises 15 freight locomotives and two passenger locomotives, each of these 17 locomotives weighing 80 tons. Although the undertaking involves transporting annually five million tons of ore over a distance of some 26 miles, the quantity of electricity which will be consumed annually at the substations will only be of the order of less than 20 million kw-hr. A single 5000-kw. turbo-generator with a total weight (including steam-turbine, generator and their common base and bearings) of only some 115 tons, often turns out this quantity of electricity in the course of a year. Only two sub-

stations (26 miles apart) are required for the undertaking, and each substation contains only two motor-generator sets, each set having a *rated* capacity of 1000-kw. and an ample *overload* capacity to carry 3000 kw. for 5 minutes at intervals. The four motor-generator sets only aggregate a total weight of some ($4 \times 45 =$) 180 tons. The only items of large consequence involved in the electrification of this undertaking are, on the one hand, the 17 locomotives, and, on the other hand, the provision of the overhead contact line, the track bonding and the positive and negative feeders.

Trailing loads of 3400 tons[5] will be hauled by two of these 80-ton locomotives (operating as a single machine) from Butte to Anaconda over a route with a maximum grade of 0.3 per cent. For such a case we no longer have the condition which, as we have seen, so greatly affects the economy of the express-passenger proposition, namely, that the weight and friction of the locomotive constitute considerable percentages of the weight and friction of the entire train. Taking the friction of the trailing load (with reasonable allowance for curves), at 4 pounds per ton, the drawbar-pull on a 0.3 per cent grade amounts to

$$(0.3 \times 20 + 4) \times 3400 = 34{,}000 \text{ lb.}$$

When returning empty, the trailing load of some 1000 tons must be drawn up maximum grades of one per cent. The tractive effort for the empty cars will be 8 lb. per ton and the drawbar pull will then be

$$28 \times 1000 = 28{,}000 \text{ lb.}$$

Obviously, even for the heavy freight service on this mountain division, the use of two of these 80-ton locomotives will give a very wide margin of excess capacity. Each 80-ton locomotive will develop continuously a tractive effort of 25,000 lb. at 15 miles per hour. For the 160-ton combination this corresponds to a continuously sustained drawbar output of

$$\frac{15 \times 5280 \times 2 \times 25{,}000}{60 \times 33{,}000} = 2000 \text{ h.p.}$$

On a level track, higher speeds will be available. At starting, the 160-ton combination will provide a tractive effort of

$$(160 \times 2000 \times 0.25 =) \ 80{,}000 \text{ lb.}$$

5. Many trains will be so much lighter as to require the use of only one 80-ton locomotive. Single locomotives will also be employed in the yards and at various points of the system as switchers and pushers.

for a 25 per cent coefficient of adhesion

$$\text{or } (160 \times 2000 \times 0.30 =) \ 96{,}000 \text{ lb.}$$

for a 30 per cent coefficient of adhesion.

This tractive effort can also be provided by a Mallet locomotive with 160 tons on drivers. The engine and tender will, however, weigh some 250 tons and the weight on each of the six driven axles amounts to

$$\frac{160 \times 2000}{6} = 53{,}500 \text{ lb.}$$

as against a weight of only

$$\frac{160 \times 2000}{8} = 40{,}000 \text{ lb.}$$

on each of the eight driven axles of the electric locomotive. Obviously on the single score of the distribution of weight, the track conditions are distinctly less severe with the electrical alternative. There is also the important advantage, in the case of the electric locomotive, that the torque is uniform and in striking contrast with the pulsating torque of the steam locomotive.

But the essential contrast as regards relative capacities is brought to light when we state that the Mallet locomotive, when burning lignite of a calorific value of some 11,000 B.t.u. per pound, can, when exerting a drawbar pull of 60,000 lb., only maintain a sustained speed of some 6.5 miles per hour. Under these conditions the locomotive will be consuming about 7500 lb. of coal per hour, and will be developing

$$\frac{6.5 \times 5280 \times 60{,}000}{60 \times 33{,}000} = 1040 \text{ drawbar h.p.}$$

If the 250-ton Mallet locomotive is hauling a 3400-ton train, then the indicated horse power will be about

$$\frac{3650 \times 1040}{3400 \times 0.75} = 1500 \text{ i.h.p.}$$

The calorific value of the lignite employed as fuel may also be expressed as

$$\frac{11{,}000}{2545} = 4.32 \text{ h.p-hr. per pound}$$

Thus the efficiency from the coal to the cylinders is

$$\frac{1500 \times 100}{7500 \times 4.32} = 4.63 \text{ per cent}$$

This efficiency estimate is on the basis of a fuel consumption of

$$\frac{7500}{1500} = 5.00 \text{ lb. of lignite per i.h.p-hr.}$$

The efficiency from the coal to the drawbar is

$$\frac{1040}{1500} \times 4.63 = 3.22 \text{ per cent}$$

The coal consumption per drawbar h.p-hr. is

$$\frac{4.63}{3.22} \times 5.00 = 7.20 \text{ lb. per drawbar h.p-hr.}$$

When, however, we take into account the coal wastefully burned during the large part of the time during which the steam locomotive is standing still, we arrive (for mountain-grade freight service), at figures of the order of from 10 to 12 or more pounds of lignite burned per drawbar h.p-hr. On the basis of 10 lb. per drawbar h.p-hr. the efficiency from the coal to the drawbar works out at

$$\frac{7.20}{10} \times 3.22 = 2.32 \text{ per cent}$$

Even when, as will usually be the case in the West, the electric proposition involves obtaining energy from hydroelectric undertakings, it is nevertheless instructive to give close attention to these efficiency and coal consumption figures, and to contrast them with the results which may be obtained with the equivalent electricity generating station in which coal fuel is employed. It has already been stated that in such a case, some 6.5 per cent of the energy in the coal burned at the generating station is delivered at the rims of the drivers. We have now seen that for the freight service in question, an electric locomotive weighing 160 tons, when compared with a steam locomotive weighing with tender some 250 tons, yields at least as great a drawbar pull at starting, since with the same weight on drivers it replaces a pulsating torque with a

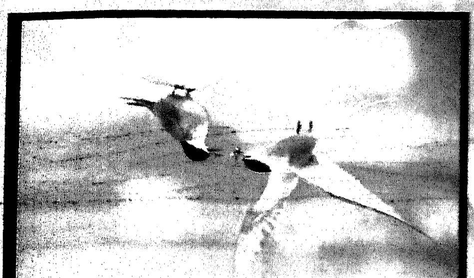
constant torque. Furthermore it can develop this drawbar pull at 14 miles per hour as against less than half this speed for the steam locomotive.

The electric locomotive requires to be manned only by one engineer, although, as a precautionary measure, an assistant engineer accompanies him on the locomotive. But when, as in the instance we have considered, a Mallet is burning 7500 lb. of coal per hour, it is considered that it is beyond the capacity of a single fireman, and for *sustained* efforts of this amount, *two* firemen should be provided. In other words, in order to work up to a consumption of 7500 lb. of coal per hour (corresponding to a speed of 6.5 miles per hour with a drawbar pull of 60,000 lb., making 1500 i.h.p.) two firemen are necessary if these conditions of speed and drawbar pull are sustained for considerable periods. Thus a crew of three men are required on the steam locomotive when only 1500 i.h.p. are developed, while on the electric locomotive just one man is actually necessary (although two are provided for the reasons stated), even when the locomotive is developing over 2000 h.p.

Capital Cost and Maintenance

Finally, as regards capital outlay and maintenance. Electric locomotives with the axles driven through gears cost a matter of some $450 per ton and the outlay for repairs and maintenance runs to some 4 cents per mile per 100 tons of weight of locomotive. The outlay for repairs and maintenance of steam locomotives is about of the order of 10 cents per mile per 100 tons of weight, and since steam locomotives are inherently incapable of the mileage per annum which can be obtained from electric locomotives, then notwithstanding that steam locomotives cost considerably less than half as much *per ton of weight*,[6] the charges per locomotive-mile for repairs and maintenance, plus interest, taxes, insurance and amortization, are inherently decidedly greater for the steam locomotive than for the electric locomotive. Electric railway engineers are satisfied that these are conservative ratios. That the values which will ultimately be established will be still

6. This ratio of costs is only in small part due to any *inherently* greater cost per ton in the case of electric locomotives. It is chiefly due to the fact that whereas several thousands of *steam* locomotives are built *every year*, there are not more than a matter of 1000 *electric* locomotives *in existence*, and only 100 to 200 are built annually. The number of steam locomotives in the United States, the United Kingdom, Germany and France aggregates over 100,000.



more favorable to the electric locomotive will only slowly be demonstrated in practise, largely for the reason that conventional methods of operating railways have been so evolved as to conform with the properties and limitations of the steam locomotive. Emancipation from these limitations will not immediately be followed by a revolution in methods of operating railways. On the contrary, the electric locomotive will for some time to come be compelled to conform to the conventions of the past. Advantage will only gradually be taken of the electric locomotive's inherently greater capacity as regards speed (in the case of freight haulage) for a given drawbar pull. It will be some considerable time before methods will so be modified that, in virtue of its greater capacity for speed in freight haulage, and in virtue of freedom from the necessity of devoting a large percentage of time to overhauling it and taking it out of service for repairs*, 50 per cent or even 100 per cent more mileage per annum will be obtained from the electric locomotive than has been found expedient with its steam predecessor. Most of the present overtime expense will be eliminated with electric operation and this in itself will effect a large saving in crew expense.

The circumstances attending specific cases vary so greatly as to render it exceedingly difficult to work out quantitative comparisons. Furthermore, a reasonable consideration for commercial interests of various sorts, requires that indications of price shall be only *relatively* correct and of the right general order of magnitude. But notwithstanding the frank admission that the figures employed in the following comparison are purposely so selected that they are only quite roughly correct, and amply conservative at the present state of the art, they nevertheless, taken *relatively*, as contrasting electric with steam working, bear a very correct ratio to one another, and will be amply sufficient for the purposes of a rough comparison.

Hypothetical Example

Let us contrast the case of employing 10 electric locomotives weighing 160 tons each, and with the entire weight on drivers,

* While a comparatively short run necessitates that the steam locomotive be temporarily withdrawn from service for several hours for adjustments, cleaning and other attentions, no such limitations obtain in the case of the electric locomotive. Moreover it can be arranged that the engineer and his assistant shall relieve one another at frequent intervals, thus maintaining their strength and alertness to a degree quite impossible for the engineer and fireman constituting the crew of a steam locomotive.

with the alternative of employing 15 steam locomotives of the Mallet type, weighing, with tenders, 250 tons each, of which 160 tons is on drivers. Let the work to be performed consist in hauling freight. Let the conditions governing the capacity per steam locomotive consist in the requirement of hauling 1400-ton trains up long 1.5-per cent grades at 6.5 miles per hour, and starting 1400-ton trains on 1.5-per cent grades, and let it be proposed that the electric locomotives shall start and haul trains of the same weight over the same grades at speeds 50 per cent greater. Let the total length of single track, including terminals and sidings, be a matter of 50 miles.

Let each electric locomotive traverse 24,000 traffic miles per annum as against 16,000 traffic miles per annum for each of the steam locomotives.[7] In both cases the total traffic amounts to 240,000 locomotive miles per annum.

When hauling a 1400-ton train up a 1.5-per cent grade at 6.5 miles per hour, the output at the drawbar is

$$\frac{6.5 \times 5280 \times 38 \times 1400}{60 \times 33{,}000} = 923 \text{ h.p.}$$

The corresponding output from the cylinders of the 250-ton steam locomotive is

$$\frac{1670 \times 923}{1400 \times 0.75} = 1450 \text{ i.h.p.}$$

On the basis of employing as fuel Western lignite of a calorific value of 11,000 B.t.u. per pound, (4.32 h.p-hr. per pound), the coal consumption may be taken at 5 lb. per i.h.p-hr. while the

7. Experience has demonstrated that an electric locomotive will be available for service every day for eleven out of the twelve months of the year, the remaining month affording a liberal margin for general repairs. During the (11/12 × 365 =) 334 days of service, even a low-speed electric locomotive hauling freight over a mountain division, will readily yield 100 miles per day. This works out at an annual mileage of 33,400. It is exceedingly conservative to cut this down to 24,000 miles, or an average of (24,000/334 =) 72 miles per day, averaged over 334 days, or (24,000/365 =) 66 miles per day, averaged over 365 days.

On the other hand, to credit each steam locomotive with (16,000/365 =) 44 miles per day, when averaged over the 365 days in the year, is to take an exceedingly high figure which is seldom if ever reached by Mallets when dealing with the class of service on which the example is based.

locomotive is hauling its train under these conditions of maximum load. Thus we have a coal consumption of

$$\frac{1450 \times 5}{6.5} = 1120 \text{ lb. per train-mile}$$

Let it be premised that the average load for the entire 16,000 traffic miles traversed by the locomotive in a year, is only one-third of this maximum load. The average coal consumption with which the locomotive must be debited per train-mile, will not, however, fall to 1120/3 = 373 lb. per train-mile, for we must make allowance for the large amount of coal burned in the course of the many hours during which the locomotive is standing still, but with fires up.[8] We shall be decidedly favoring the steam locomotive in this comparison if we debit it with an average coal consumption of 560 lb. per locomotive-mile for the 16,000 miles which it travels annually. On the basis of $2.50 per ton, the fuel cost amounts to

$$\frac{560}{2000} \times 2.50 = \$0.685 \text{ per train-mile}$$

In the case of the electric locomotive we shall supply the draw-bar pull at a 50 per cent higher speed. Consequently on the 1.5-per cent grades, the power at the drawbar will be

$$923 \times 1.5 = 1390 \text{ h.p.}$$

8. At page 53 of Ripley's "Railroad Rates and Regulations" (Longmans, Green and Co., 1912), the author, in discussing the cost of fuel for motive power, writes: "This item, amounting in 1905 to no less than $156,000,000 for the railroads of the United States, was the largest in the budget, constituting 11 per cent of all operating expenses. Yet brief consideration shows that even here much of this expense is constant and invariable. A locomotive will burn fully one-third as much coal merely to move its own weight as to haul a loaded train. Five to ten per cent of its total daily consumption is required merely for firing up to the steaming point. Twenty-five to 50 pounds of coal per hour go to waste in holding steam pressure while a freight train is waiting on a siding. Every stop of a train going thirty miles per hour dissipates energy enough to have carried it two miles along a level road. In brief, expert evidence shows that of this important expenditure for coal 30 to 50 per cent is entirely independent of the number of cars or the amount of freight hauled."

The output at the drivers of the electric locomotive will be

$$\frac{1560}{1400} \times 1390 = 1550 \text{ h.p.}$$

The input to the locomotive will be

$$\frac{1550 \times 0.746}{0.87} = 1330 \text{ kw.}$$

The input to the substations per train-mile will be

$$\frac{1330}{0.93 \times 0.78 \times 6.5 \times 1.5} = 188 \text{ kw-hr.}$$

But this input corresponds to the load on the ruling grade. We have already premised an average load equal to one-third of the maximum load. Consequently we have

Average input to substations $= \frac{188}{3} = 63$ kw-hr. per locomotive-mile.

On the basis of a price of one cent per kw-hr. delivered to the substations, the average cost of the electricity per locomotive-mile comes to

$$63 \times 0.01 = \$0.63$$

This is in comparison with the average cost of $0.685 for fuel per locomotive-mile corresponding to a price of $2.50 per ton for lignite.

The item of wages for the locomotive crew, will be taken at 20 cents per mile both for the steam locomotive, and for the electric locomotive.

Appropriate *relative* figures for repairs and maintenance are ($10 \times 2.5 =$) 25 cents per mile for the steam locomotive, and ($4 \times 1.6 =$) 6.4 cents per mile for the electric locomotive.

As to capital outlay for locomotives, $45,000 for each steam locomotive can fairly be compared with $72,000 for the electric locomotive. This is a fair *ratio* and suggests a reasonable order of magnitude. In spite of the simplicity and strength of the electric locomotive, let us credit it with only the same life, in years, as the complicated and vulnerable steam locomotive and let us take the life as 15 years. Let taxes and insurance amount to 3 per cent. Consequently as annual charges on the capital

outlay for locomotives, we may fairly take $(5 + 4.6 + 3) = 12.6$ per cent in each case. This comes to \$5,670 per annum for each steam locomotive and \$9,060 per annum for each electric locomotive. These figures reduce to

$$\left(\frac{567{,}000}{160{,}000}\right) = 35.4 \text{ cents}$$

per mile for the steam locomotive and

$$\left(\frac{906{,}000}{24{,}000}\right) = 37.8 \text{ cents}$$

per mile for the electric locomotive.

Thus for the five component costs which we have considered, the results are as follows:

	Per locomotive-mile Steam	Electric
I.—Fuel	\$0.685	——
II.—Electricity	——	\$0.630
III.—Wages of locomotive crews	0.200	0.200
IV.—Repairs and maintenance of locomotives	0.250	0.064
V.—Interest, taxes, insurance and amortization	0.354	0.378
Totals of above 5 items	\$1.489	\$1.272

These five items amount, for the 240,000 locomotive miles per annum, to the following annual outlays:

Steam	240,000 × 1.489 =	\$357,000
Electric	240,000 × 1.272 =	306,000
Difference in the totals of the 5 items		\$51,000

To illustrate the sensitiveness of the result on the prices of coal and electricity respectively, it should be noted that with coal at \$2.80 per ton and electricity at 0.80 cents per kw-hr., the difference in the totals of these 5 items for steam and electricity increases from the above result of \$51,000 to \$102,000.

The wages of substation attendants and linemen will only absorb a small portion—say \$15,000—of the above balances, leaving the large remainder available to be applied to liquidating the capital outlay for substations and for feeders and contact conductors and for track structures and bonding.

No degree of exactness is claimed for the above cost comparison, but it *is* claimed that the results are very indicative of large

commercial advantages in the electric operation of sections of main-line railways, especially in instances where electricity can be purchased at the substations at a cost of not much over one cent per kw-hr. It is often remunerative to large hydroelectric undertakings to supply electricity to railways at prices below one cent per kw-hr. at the substations. The dependence of the soundness of the proposition on the cost of coal and the price at which electricity can be obtained, is indicated by the result to which allusion has already been made, that the saving, in the case examined, goes up from $51,000 per annum for coal at $2.50 per ton and electricity at one cent per kw-hr. to $102,000 per annum for coal at $2.80 per ton and electricity at 0.8 cent per kw-hr.

The calculations also show equally definitely that with coal at, say, $2.00 per ton and electricity at two cents per kw-hr. or thereabouts, it would be futile to consider electrification as a means of increasing the net earnings with traffic of this nature.

Consequently the merits of a proposal to electrify such a line may often be contingent upon the presence in the vicinity of a large system supplying electricity for miscellaneous power and lighting. From such a system the electricity required by the railroad could often be supplied profitably at less than one cent per kw-hr. delivered at the substations, as against a cost which might run up to two cents or more, if the railroad had to provide its own power house for supplying exclusively the small quantity of electricity at poor load factor, required for so sparse a service of trains.

Let us, however, return to the consideration of the case on the assumption that the railroad can purchase the required electricity at some such price as 0.8 cent per kw-hr. delivered at the substations.

The total quantity of electricity annually required at the substations in the above hypothetical case, is

$$240{,}000 \times 63 = 15.1 \text{ million kw-hr.}$$

The cost of substations, feeders and contact conductors, in fact, of all work, apparatus, buildings, structures and materials required for electrification, in addition to the 10 locomotives, would, for an undertaking of this magnitude, only amount to a matter of some $600,000, more or less. Of course the precise circumstances of each case would greatly affect this total.

It may have been observed that no reference has yet been made

in this paper to the weight of the electrical apparatus constituting the motive power and control equipment of the locomotives. For the examples considered, there has been no occasion to introduce this factor. The weight of the complete electrical equipment for the 2400-volt system runs only to a matter of some 55 lb. per horse power of *continuous* capacity. In fact the electrical equipment of the Butte locomotive weighs only 53,000 lb. out of a total weight of 160,000 lb. Each 80-ton locomotive has a *continuous* capacity for maintaining a drawbar pull of 25,000 lb. at 15 miles per hour. This corresponds to a *drawbar* output of 1000 h.p. or an output *at the drivers* slightly in excess of 1000 h.p. This brings the weight down to some 50 lb. per horse power of *continuous* output *at the drivers*.

The significance of the low weight of electrical equipment is that there is ample margin to obtain the horse power capacity required at high speeds without exceeding the weight on drivers necessary for obtaining the required drawbar pull.

Electrification of a 96-mile Single-Track Mountain-Grade Division of a Main-Line Railway

Let us now consider the electrification of a link in a main-line railway, which consists of a mountain-grade division 96 miles long. At certain seasons of the year there is experienced at this link a congestion of freight traffic of so severe a nature that it becomes necessary to divert to other routes of much greater length a large percentage of the available freight.[9] The division is single-tracked with 15 sidings at an average distance of six miles apart, thus dividing the 96 miles into sixteen sections of varying length but averaging six miles each. The character of the route is such that double tracking would involve enormous expense. This is often the case on mountain-grade divisions.

The trains negotiate an altitude of 3800 ft. in 48 miles and return to the original level in the remaining 48 miles. Thus the average gradient is

$$\frac{3800 \times 100}{48 \times 5280} = 1.5 \text{ per cent}$$

The ruling gradient is 2.2 per cent. There are occasional 2.5 per cent gradients but these are so short that they may be dealt

9. While the extent of the freight congestion assumed in this example is doubtless extreme, the rapidly expanding freight business of the country is leading to conditions of this order of seriousness.

with as " momentum gradients " and are not determinants in arriving at the correct powering of the trains.

It is proposed that electric locomotives shall carry over this division trains of weights ranging from 900 to 1800 tons (exclusive of the weights of the locomotives), and that while ascending, the average speed between stops shall be 12 miles per hour. Where the grade is in excess of the average value of 1.5 per cent, the speed will be less than 12 miles per hour, and for gradients of less than 1.5 per cent the speed will be in excess of 12 miles per hour. The range of variation will, however, be only of the order of from 9 to 15 miles per hour.[10] Ascending trains will be operated over the main track, and the number of stops will be reduced to a minimum. Descending trains will be operated at slightly higher speeds in order that they may be out of the way in the sidings when the ascending train arrives. Obviously on the basis of an average speed of 12 miles per hour, the 96-mile journey would require 8 hours were the ascending train to make no stops. On this *admittedly theoretical* hypothesis, and with trains in each direction simultaneously occupying alternate sections between sidings, the 96-mile division could contain simultaneously 8 trains traveling in each direction, (or a total of 16 trains), and trains could be sent into the division from each end of the division at the rate of one per hour. Thus there could be 24 trains passed over the division in each direction per day. This leads us to the (theoretically) limiting capacity of

$$48 \times 96 = 4600 \text{ train-miles per day}$$

In *practise*, however, after making reasonable allowances for unequal distances between sidings, variations in speed due to varying grades and curves, delays at the terminals of the 96-mile division, inevitable stops even of the ascending trains, and other causes for irregularity, the practical limit of the capacity of the division may be taken as of the order of

$$(0.75 \times 48) \times 96 = 36 \times 96 = 3460 \text{ train-miles per day}$$

This is on the basis that there shall be only (36/2 =) 18 trains instead of 24 in each direction per day.

Traffic of this intensity will, however, occur only during 100 days in the year. For the remaining 265 days, the freight to be transported will require only the equivalent of twenty-four 900-

10. A few passenger trains will be sent over the division every day. But to simplify the investigation, it will be assumed that these are taken into account by their equivalent in freight traffic.

ton trains per day, or twelve 900-ton trains in each direction, whereas for the 100 days of dense traffic, the 36 trains per day will each represent 1800 tons behind the drawbar.

Thus there will be transported annually over the division a total tonnage behind the drawbar, amounting to $100 \times 36 \times 1800 + 265 \times 24 \times 900$[11] $= 6,500,000 + 5,700,000 = 12,200,000$ tons, or $96 \times 12,200,000 = 1,170,000,000$ ton-miles.

Making reasonable allowance for the weight of the cars and for empty and lightly-loaded cars, we may take one-half of this load behind the drawbar as revenue tonnage. The paying load will thus amount to 6,100,000 tons per annum or $96 \times 6,100,000 = 585,000,000$ ton-miles.

On the basis of an average rate of 0.75 cent per ton-mile, the gross receipts amount to $585,000,000 \times 0.0075 = \$4,390,000$ per annum or \$45,600 per mile of railway.[12]

The requirements of the railway as regards number and size of locomotives must be based on the seasons of dense traffic. On the ruling grade of 2.2 per cent, an 1800-ton train will require a drawbar pull of $(2.2 \times 20 + 8) \times 1800 = 94,000$ lb.

DRAWBAR PULL

Adding a further 36 per cent in order to have a safe margin for increased journal friction in cold weather, for adverse winds and for severe curves, we arrive at the value of $1.36 \times 94,000 = 128,000$ lb. as the drawbar pull which should be available when dealing with 1800-ton trains on this division. Providing a locomotive at each end of the train then each of these two locomotives will require to have sufficient reserve capacity for exerting a drawbar pull, or push, of

$$\left(\frac{128,000}{2}\right) = 64,000 \text{ lb.}$$

On the basis of a coefficient of adhesion of 0.20, each locomotive must have a weight on drivers of

$$\frac{64,000}{0.20 \times 2000} = 160 \text{ tons}$$

11. It is shown on the following page that the 1800-ton trains will require two locomotives and the 900-ton trains, one locomotive, consequently the annual locomotive mileage is equal to $96 \times 100 \times 36 \times 2 + 96 \times 265 \times 24 \times 1 = 690,000 + 610,000 = 1,300,000$.

12. It is recognized that this is a high figure, but it is consistent with the hypothesis of a congested link in an extensive railway system.

Thus, so far as relates to the provision of the required tractive effort, the 160-ton Butte locomotives already described in this paper are appropriate for use on this 96-mile mountain-grade division.

The drawbar pull, when accelerating from rest (at the rate of one-tenth of a mile per hour per second) on the average gradient of 1.5 per cent, will be $(1.5 \times 20 + 10 + 10) \times 1800 = 90{,}000$ lb. or only 69 per cent of the *maximum* drawbar pull (128,000 lb.) available with a coefficient of adhesion of 0.20. When desirable, an acceleration of over a quarter of a mile per hour per second may be imparted to an 1800-ton train on the average grade.

When working the line to its utmost capacity, (*i.e.*, with a descending train in every other length between sidings and an ascending train in each intermediate length between sidings (each train having a weight, exclusive of locomotives, of 1800 tons) there would be simultaneously traversing the division 16 trains and 32 locomotives. It has already been explained that practical limitations will cut this down, either as regards the number of trains simultaneously present in the division or as regards the maintenance of the journey speed of 12 miles per hour for the 96-mile run. The actual shortage will be due partly to each of these two factors. With due allowance for additional locomotives to be available in making up trains at the terminals before entering the 96-mile division, and for spare locomotives, there should be provided a total equipment of 48 locomotives of 160 tons each.[13] This total number of locomotives is determined upon to meet the requirements of the 100 days of dense traffic. A considerable percentage of the 48 locomotives will be in excess of the requirements of the remaining 265 days of the year and will be enforcedly idle.

When handling an 1800-ton train at a speed of 12 miles per hour on a 1.5-per cent grade, we have

$$\frac{12 \times 5280 \times 90{,}000}{60 \times 33{,}000} = 2880 \text{ h.p. at the drawbar}$$

13. With the mean value of 28 locomotives (14 trains) simultaneously occupying the 96-mile section, there remain (48—28) = 20 locomotives. With four undergoing repairs, we have 16 available at termini, 8 at each end. Since these locomotives are double-ended, there will be much less time occupied than with steam locomotives in making up trains in readiness to be sent into the division.

This will be subdivided between the two 160-ton locomotives, and each will deliver 1440 h.p. at the drawbar, or

$$\frac{900 + 160}{900} \times 1440 = 1700 \text{ h.p.}$$

at the rims of the drivers.

Each locomotive has eight motors (one on each of the eight driven axles); consequently the output per motor when ascending the 1.5 per cent grade at 12 miles per hour, is 1700/8 = 213 h.p.

Since this output of 213 h.p. is the average load, the work is seen to be well within the capacity of the equipment on the Butte locomotives, for on those locomotives each motor has a continuous capacity of 250 h. p. when cooled by the forced circulation of air through it.

Weight behind Drawbar

In making up an estimate of the total annual traffic, we have arrived at the figure of 12,200,000 tons as the weight behind the drawbar passing annually over the division. Since we employ a 160-ton locomotive for every 900 tons, we shall have

$$\frac{12{,}200{,}000}{900} = 13{,}600 \text{ locomotive journeys}$$

over the division per annum,

or $$\frac{13{,}600}{48} = 284 \text{ journeys per locomotive}$$

Thus as an average for each one of the 48 locomotives we have a performance of 96 × 284 = 27,200 miles per annum.[14]

This is not to be taken as indicating an average mileage of 27,200/12 = 2260 miles per locomotive for *each* of the 12 months in the year. On the contrary, during the months of heavy traffic this will be greatly exceeded and during the months of light traffic a considerable proportion of the locomotive equipment will be idle and the average mileage per month per locomotive will fall greatly below 2260 miles.

14. In the footnote No. 11, we have already arrived at the figure of 1,300,000 locomotive miles per annum. We have 1,300,000/48 = 27,200 miles per locomotive per annum, thus checking the above result in the body of the text.

At the speed of 12 miles per hour (96/12 =) 8 hours would be occupied by the journey, and each locomotive would spend $286 \times 8 = 2288$ hours per annum on the 96-mile division. But what with the decreased speed due to delays and the large amount of time occupied at terminals in making up trains, each locomotive would be in service with its crew for $1.5 \times 2288 = 3440$ hours. On the basis of eight-hour shifts and two men per crew, and an average wage of $6.00[15] per day, the wages per locomotive amount to

$$\frac{3440}{8} \times 2 \times 6.00 = \$5150 \text{ per annum}$$

$$\text{or } \frac{515{,}000}{27{,}200} = 18.9 \text{ cent per locomotive-mile}$$

Repairs and maintenance per locomotive amount to $0.04 \times 1.6 \times 27{,}200 = \$1740$ per annum or $4 \times 1.6 = 6.4$ cents per locomotive-mile.

On the rough basis of $450 per ton, we may take the price of each locomotive as $160 \times 450 = \$72{,}000$.

The 48 locomotives run to a total inital outlay of $48 \times 72{,}000 = \$3{,}460{,}000$.

Taking interest, taxes, insurance and amortization as aggregating 12.6 per cent on the investment for locomotives, these charges for each locomotive amount to $72{,}000 \times 0.126 = \$9060$ per annum.

COST PER LOCOMOTIVE

(This is on the basis of interest at 5 per cent, taxes 1.5 per cent, insurance 1.5 per cent, and a life of 15 years).

Thus we have, per electric locomotive per annum

I.—Wages of locomotive crews	$5150
II.—Repairs and maintenance	1740
III.—Interest, taxes, insurance, amortization	9060
Total of above three items	$15,950

For the 48 locomotives, this comes to a total of

$$48 \times 15{,}950 = \$766{,}000.$$

15. The crew of each locomotive will consist of an engineer and his mate. The latter accompanies the engineer on general principles relating to safety in the event that the engineer should be incapacitated from any cause. The engineer will receive a higher wage than this average of $6.00 for the crew, and the mate will receive less than this average. The average figure of $6.00 is high when taken in connection with the schedules at present in force, but its employment in this comparison is consistent with the purpose to favor steam-locomotive methods at all points where the reasonableness of the assumptions could be questioned.

Let us estimate the amount of electricity consumed by the ives. On the ascent, the power averages 2880 h.p. at ,bar or 3400 h.p. from the motors.

verage consumption by the locomotives works out at

$$\frac{3400 \times 0.746}{0.87} = 2920 \text{ kw.}$$

g the ascent, electricity is drawn from the line only during) 4 hours, notwithstanding that the ascent is only ished in a greater time than this.

nergy consumed during the ascent is

$$4 \times 2920 = 11,700 \text{ kw-hr.}$$

turn of energy to the line will be credited to the loco during the descent; on the contrary, an allowance of 500 ill be made for occasional application of power.

y consumed by locomotives during descent = 500 kw-hr.

consumption of energy by locomotives per round trip with 1800 ton trains,

$$11,700 + 500 = 12,200 \text{ kw-hr.}$$

900 ton trains, the consumption per journey will be

$$\frac{12,200}{2} = 6100 \text{ kw-hr.}$$

are $100 \times 36 = 3600$ journeys per annum with 1800 s and $265 \times 24 = 6360$ journeys per annum with 900 ns.

he total consumption at the locomotives is

$$12,200 + 6360 \times 6100 = 44,000,000 + 39,000,000$$

$$= 83,000,000 \text{ kw-hr. per annum}$$

sing this by 25 per cent *i.e.*, by 21,000,000 kw-hr., to 00 kw-hr. per annum to allow for terminal service d for heating of locomotives and as a margin of safety, g at 0.93 the annual efficiency from the substation ans, we obtain for the output from the substations

$$\frac{104}{0.93} = 112 \text{ million kw-hr. per annum}$$

The annual over-all efficiency of the substations may be taken at 78 per cent. Consequently the input to the substations is

$$\frac{112}{0.78} = 144 \text{ million kw-hr. per annum.}$$

On the basis of a price as *delivered to* the substations, of 0.70 cent per kw-hr., the outlay for electricity is

$$144{,}000{,}000 \times 0.0070 = \$1{,}010{,}000 \text{ per annum.}$$

Per locomotive, this works out at

$$\frac{1{,}010{,}000}{48} = \$21{,}000$$

or

$$\frac{2{,}100{,}000}{27{,}200} = 78 \text{ cents per locomotive-mile.}$$

As to the overhead contact line, the rail bonding and the feeder copper, these will be covered liberally by an outlay of $8500 per mile. Allowing for sidings, the total outlay will be $900,000.

Finally, there will be required four substations, each for an annual output of 28,000,000 kw-hr.

On the basis of a load factor of 0.25, the *maximum* load on each substation will be

$$\frac{28{,}000{,}000}{8750 \times 0.25} = 12{,}800 \text{ kw.}$$

The *average* load per substation will be only some

$$\left(\frac{28{,}000{,}000}{8750}\right) = 3200 \text{ kw.}$$

These substations will cost, complete, with step-down transformers and motor-generators, some $160,000 per substation or $640,000 for the four substations.

Taking interest, maintenance, taxes, insurance, amortization, and labor for attendants, and linemen, as amounting to 16 per cent[16]

16. The criticism may be raised that this $246,000 should be considered in detail. To do so would only introduce uninteresting calculations. The item is relatively so small that it can consistently be dismissed without further comment than to point out that it includes an allowance of some $50,000 for wages of substation attendants, inspectors and linemen.

on this outlay of $900,000 + 640,000 = $1,540,000, we arrive at a charge of

$$(0.16 \times 1{,}540{,}000) = \$246{,}000 \text{ per annum}$$

or

$$\frac{246{,}000}{48} = \$5130 \text{ per locomotive,}$$

or

$$\frac{513{,}000}{27{,}200} = 18.8 \text{ cents per locomotive mile.}$$

Thus for those annual outlays which are other for electric working than they are for steam working, we have:

Loco. wages, repairs and maintenance interest, taxes, insurance, amortization	$766,000	per	annum
Electricity	1,010,000	"	"
Substations and distributing system	246,000	"	"
Total	$2,022,000	"	"

COST WITH STEAM

Now how does the case stand with steam? Let us assume that a 250-ton Mallet locomotive can handle a load of 600 tons behind the drawbar over this division with the same speed when in motion, as the 160-ton electric locomotive with its 900-ton load.[17] Then when, as at times of densest traffic, it is desired to carry freight in 1800-ton trains, we shall require three 250-ton Mallets as against two 160-ton electric locomotives.

The average load at the drawbar, if equally subdivided amongst the three Mallets, is

$$\frac{2880}{3} = 960 \text{ h.p. per Mallet}$$

The drawbar pull is equal to

$$\left(\frac{960 \times 33{,}000 \times 60}{12 \times 5280}\right) = 30{,}000 \text{ lb.}$$

17. This is crediting the Mallets with a higher speed for such loads than they can maintain. Nevertheless it is "leaned" to err on the side of favoring the steam locomotive whenever there is room for divergence of opinion.

This corresponds to an output from the cylinders of

$$\frac{(600 + 250) \times 960}{600 \times 0.75} = 1810 \text{ i.h.p.}$$

The fuel will be Western lignite of a calorific value of 11,000 B.t.u. (4.32 h.p-hr.) per pound and the consumption will be five lb. per i.h.p.

The coal consumption for a speed of 12 miles per hr. and for 600 tons behind the drawbar, thus amounts to

$$\frac{1810 \times 5}{12} = 755 \text{ lb. per locomotive-mile.}$$

But this result is arrived at on the basis that there is no wasteful consumption during stops. Unlike the electric locomotive, however, several stops will be necessary for taking on water and for coaling, and the consumption during the ascent will be increased to at least 850 lb. per locomotive-mile, or

$$48 \times 850 = 40{,}800 \text{ lb. for the ascent.}$$

The descent will occupy some 5 to 7 hours. While the power required for propulsion will be negligible for most of the descent, nevertheless, steam must be maintained in the boilers, and also, owing to the high frictional resistance of Mallet engines, power will be required for all grades materially lower than the average value of 1.5 per cent. Let us take the coal consumption as 400 lb. per hour, or ($6 \times 400 =$) 2400 lb. for the 48-mile descent.

Thus the total coal consumption for the locomotive for the 96-mile journey, comes to

$$40{,}800 + 2400 = 43{,}200 \text{ lb.}$$

This should be increased by 20 per cent to cover the coal burned by the switching engines and also by the Mallets during terminal movements before entering and after leaving the 96-mile division, bringing the total to

$$\begin{aligned} 1.20 \times 43{,}200 &= 52{,}000 \text{ lb.} \\ &= 26 \text{ tons} \end{aligned}$$

This is an average of

$$\frac{52{,}000}{96} = 540 \text{ lb. per locomotive-mile}$$

for the 96-mile journey.

At \$2.40 per ton, we have a full cost of

$$\left(\frac{540}{2000} \times 240\right) = 65 \text{ cents per locomotive-mile.}$$

Of course it is to be understood that the terminal operations are not executed by Mallets but by switching locomotives. But to simplify the calculations, the equivalent outlay is taken in terms of Mallets.

RUNNING TIME

Attention must now be drawn to the consideration that with the delays inherent to steam locomotive operation, even on the favorable assumption that the speed with three 250-ton steam locomotives and an 1800-ton train may, when running, be taken equal to the speed of two 160-ton electric locomotives and an 1800-ton train, nevertheless, the running time for the 96-mile journey, (together with the increased time consumed in making up trains at terminals with single-ended and cumbersome steam switching engines as compared with double-ended and simple electric locomotives), will certainly be at least 50 per cent greater. Thus for the 100 days of dense traffic when the division is worked to its utmost capacity, the train mileage is cut down to two-thirds of that obtained with electric operation. The limiting capacity of the line is thus reduced to

$$\frac{2}{3} \times 6{,}500{,}000 + 5{,}700{,}000 = 4{,}300{,}000 + 5{,}700{,}000 = 10{,}000{,}000 \text{ tons}$$

$$\text{or } 96 \times 10{,}000{,}000 = 960{,}000{,}000 \text{ ton-miles.}$$

Again taking one-half as revenue load and crediting it with an average rate of 0.75 cent per ton-mile we ascertain the gross receipts to be

$$480{,}000{,}000 \times 0.0075 = \$3{,}600{,}000 \text{ per annum,}$$

$$\$37{,}500 \text{ per mile of railway.}$$

We have seen that for 600 tons behind the drawbar of each locomotive, the coal consumption to be debited to the entire journey works out at 540 lb. per locomotive mile.

This is

$$\frac{540}{300} = 1.80 \text{ lb. per revenue ton-mile,}$$

or

$$\frac{1.80}{2000} \times 480{,}000{,}000 = 432{,}000 \text{ tons per annum.}$$

hours, the coal consumption amounts to 8200 lb. per hour; if in 6 hours, 6800 lb. per hour. It is often maintained that *two* firemen should be provided when it is required to fire such great hourly quantities of coal.

Repairs and maintenance per locomotive amount to

$$0.10 \times 2.5 \times 18{,}100 = \$4250 \text{ per annum}$$

(This is on the basis of $10 \times 2.5 = 25$ cents per locomotive-mile)

Thus per steam locomotive per annum we have

I.	Wage of locomotive crews.............	$3380	per annum
II.	Repairs and maintenance............	4250	" "
III.	Interest, taxes, insurance, amortization.	5660	" "
	Total of above three items............	$13,290.	" "

For the 72 locomotives we have

$$72 \times 13{,}290 = \$956{,}000.$$

Bringing together the annual outlays which should be compared with those previously set forth as relating to equivalent operation by electricity, we have

Locomotive wages, repairs, maintenance, interest, taxes, insurance, and amortization............................	$956,000.	per annum
Coal............................	1,040,000	" "
	$1,996,000*	" "

But, whereas the electrical outlay of $2,022,000 per annum was associated with a revenue of $4,390,000 per annum, leaving a difference of $2,368,000 per annum to be applied to the outlays common to both systems and to reserves, the corresponding steam outlay of $1,996,000 per annum is associated with the reduced revenue of only $3,600,000 per annum, leaving a difference of only $1,604,000 to be applied to residual outlays and to reserves.

$$\frac{1{,}604{,}000}{2{,}368{,}000} = 0.68$$

Thus the residual amount with steam is only 68 per cent of that with electricity.

*No charge is made to cover outlays for round-houses, water tanks, structures for coal stores and other works incident to steam locomotive operation and not required when electric locomotives are adopted.

It will be agreed that the correct basis for estimating the commercial results to accrue from electrical operation is to compare all those items which are affected by the use of electricity instead of steam. This is, however, inconsistent with the retention of the forms which have become customary in analyzing the results of steam operation. Consequently, as of probable interest, the locomotive operating expenses per locomotive-mile are tabulated below.

	Operating expense in cents per locomotive-mile	
	Steam locomotive	Elec. locomotive
Fuel	65.0	0
Electricity	0	78.0
Repairs	20.0	5.6
Wages	18.7	18.9
Engine house expenses	3.5	0
Lubricants	0.9	0.5
Stores	0.6	0.3
	108.7	103.3

These figures only apply to the particular 96-mile mountain division which has constituted the subject of our analysis and to the particular prices employed for coal ($2.40 per ton) and electricity (0.70 cent per kw-hr.)

For the electric proposition there is an average load of 900 tons behind the drawbar for every electric locomotive. But from the data previously given we see that the average load behind the drawbar for the steam locomotive is only

$$\frac{960{,}000{,}000}{1{,}300{,}000} = 740 \text{ tons.}$$

Consequently to reduce the locomotive operating costs to comparable terms let us take as a standard of reference 100 tons behind the drawbar. We then have steam locomotive operating costs per mile

$$= \left(\frac{108.7}{7.40}\right) = 14.7 \text{ cents per 100 tons behind drawbar.}$$

Electric locomotive operating costs

$$= \left(\frac{103.3}{900}\right) = 11.6 \text{ cents per 100 tons behind drawbar.}$$

Let us look at the costs per locomotive-mile, per total train-mile and per 100-ton-miles behind the drawbar for the 1800-ton

train which we have more particularly investigated. This required three 250-ton Mallets or two 160-ton electric locomotives, bringing up the total train weights in the two cases to $(3 \times 250 + 1800 =)$ 2550 tons and $(2 \times 160 + 1800 =)$ 2120 tons respectively.

The results are set forth in the following table:

	Operating expense in cents per mile					
	Per steam locomotive	Per elec. locomotive	Per steam train (3 locomotives)	Per elec. train (2 locomotives)	Steam operation: Per 100 tons behind drawbar	Electric operation: Per 100 tons behind drawbar
Fuel or electricity	65.0	78.0	195.0	156.0	10.8	8.7
Repairs........	20.0	5.6	60.0	11.2	3.3	0.6
Wages.........	18.7	18.9	56.1	37.8	3.1	2.1
Engine house expense........	3.5	0	10.5	0	0.6	0
Lubricants.....	0.9	0.5	2.7	1.0	0.2	0.1
Stores.........	0.6	0.3	1.8	0.6	0.1	0.1
Totals......	108.7 per loco. mile	103.3 per loco. mile	326.1 per train mile	206.6 per train mile	18.1 per 100 ton-miles behind the drawbar	11.6 per 100 ton-miles beind the drawbar

A paper presented at the 283d Meeting of the American Institute of Electrical Engineers, New York, May 20, 1913.

TRUNK LINE ELECTRIFICATION

BY CHARLES P. KAHLER

The object of this paper is to show the effect of the substitution of electric motive power for steam, upon the operation of a railroad, and the comparative cost of operating a railroad by steam and electric power; also to outline general railroad conditions and show whether the return on the large investment necessary for the electrification of a steam railroad (by reason of the lower electric operating expenses and increased passenger earnings) will be likely to warrant operation by electric power.

General

The great objection to operating many of the large steam railroads by electric power is the extremely heavy investment necessary for the electric apparatus and equipment. The ability of the steam locomotive to handle railroad traffic in a very reliable, and, I may also say, expeditious manner, is very well known, but up to date, railroad managers either have not been convinced that electric motive power is as reliable as steam power or else they do not believe that the improvement in the railroad service or the saving in operating expenses resulting from electric operation will be great enough to warrant the heavy expenditures necessary. On most railroads, bonds would have to be issued to cover the cost of electrification, and the return on the investment, by reason of the lower electric operating cost, would have to be great enough to pay the interest and sinking fund on the bonds, and leave a reasonable profit besides.

Reasons for Past Electrification Work

Very little of the past work of steam railroad electrification was done on account of the financial return expected on the money

so expended. It was the ability of the electric locomotive to accomplish or do some special work not possible with the steam locomotive that caused most of the past work to be done. The first heavy electric railroad work in this country was on the B. & O. R.R., where the electric locomotives were substituted for steam locomotives to do away with the smoke troubles in the long Belt tunnel extending under the heart of Baltimore. The smoke trouble with steam locomotives has, in fact, been one of the most important reasons for the past progress in heavy electric railroad work. Steam locomotives, with their smoke and gases, could hardly do the work of the Pennsylvania electric locomotives operating through the tunnels into New York. The smoke nuisance is also the principal reason that the electrification of the Chicago terminals is being considered at present.

Results of Past Heavy Electrification Work

Irrespective of what caused the past heavy electric railroad work, the actual operation of large electric locomotives showed that they could in some ways handle railroad traffic more advantageously than steam locomotives. Also, it was found that electric locomotives were as reliable in operation as steam locomotives. In fact, the published records of the steam and electric locomotives of the New York Central Railroad, the New York, New Haven & Hartford Railroad, and the Pennsylvania Railroad, indicate that electric locomotives are probably even more reliable in operation than steam locomotives. The published records of the above roads also indicate that the quantity of fuel required to generate power in a steam-electric plant for railroad operation is much less than the fuel required by steam locomotives in the same service. Also, the locomotive repair expense was found to be much less on electric locomotives than on steam locomotives.

Further, as the electric locomotives do not have to bother with taking fuel and water, nor have a boiler or fire-box to be cleaned out, they are nearly always ready for service, and also take less time to handle trains than steam locomotives, especially on long runs. The perfection of the multiple unit control made the number of driving units which could be controlled by one man practically unlimited and, consequently, it was possible to make the size of electric locomotives much greater than steam locomotives with the boiler limitations.

The large saving in operation and other advantages which it

was evident would result from electric railroad operation, caused the manufacturers and builders of steam locomotives to make many marked improvements in the steam locomotive. The Mallet and Mikado types of locomotive, with all the refinements for economic operation, resulted partly from the competition between the steam and the electric locomotive. However, the limitations imposed by the boiler of a steam locomotive are still a big disadvantage, as any increase in tractive power of a steam locomotive can only be had by lowering the speed.

Another important point in connection with electric operation was brought out by the great success of the interurban electric railways. The frequent passenger train service, and other advantages possible on the electric railways, caused a large increase in the local passenger traffic. The passenger earnings on these interurban electric railways soon after beginning operation became much greater than had been obtained from the same territories by steam-operated railroads.

The gasoline motor car and the gas-electric motor car would probably not have been developed were it not for the trolley lines taking local passenger business away from the steam railroads. These have been successful as far as operation goes, but although some of the published costs of operation are lower than steam train operation, I know of several cases where the operating and maintenance costs of the gasoline motor cars differ very little from those of the three-car steam trains. The gasoline cars are not as reliable as a steam locomotive, and I doubt if the gas-electric cars are much better, although they are probably better fitted to handle traffic where frequent stops are necessary than the gasoline cars.

Effect of the Physical Characteristics of a Railroad on the Operating Expenses

The grades, curvature and other physical characteristics of a railroad have a very important influence upon its operating expenses and are usually very carefully studied by railroad men with a view of cutting down operating expenses. The reduction in the number of freight trains by cutting down the ruling grade is one way of reducing operating expenses. The elimination of helper engine districts, shortening of distances, taking out curvature, and lessening the rise and fall of grades, are other ways in which a great deal of money is now being expended on steam railroads to lower the operating costs.

of the inability of the boiler to supply continuously the necessary steam. On the other hand, the electric locomotive can not continuously exert the high tractive effort shown by the curve at low speeds, without overheating. The maximum tractive effort which can be continuously exerted by the electric locomotive with safety is 34,600 lb. at a speed of 16 miles per hour. Below this speed the high tractive efforts shown can only be used for certain periods of time. Thus, for one hour, 45,000 lb. tractive effort can be exerted without overheating the motors, with the speed at about 14 miles per hour.

At starting, as much as 55,000 lb. can be exerted by the electric locomotive, while the steam locomotive can, under favorable conditions, only exert a tractive effort of about 43,000 lb. at starting. One of the causes of the higher power of the electric freight locomotive at starting is that all its weight, 220,000 lb., is on the drive wheels, while although the steam locomotive with loaded tender weighs 185 tons, it has only 187,000 lb. on the drive wheels. Also the coefficient of adhesion is greater for an electric locomotive than for a steam locomotive.

The foregoing shows the characteristics of steam and electric locomotives and should give some idea of their respective abilities to handle the traffic of a steam trunk line railroad. As stated before, the weight of the steam freight trains is generally determined by the ruling grades. As an electric locomotive can exert a high tractive effort for short intervals without dangerous overheating, the average grades, which are usually much lower than the ruling grades for steam operation, have more to do with determining the weight of electrically operated freight trains. Consequently, an electric freight locomotive can usually haul much heavier trains than the steam freight locomotive over the undulating grades usual on most steam railroads.

On some engine districts the weight of freight trains is governed by the starting grades. Here also the electric freight locomotive has the advantage, as all or nearly all the weight is on the drive wheels and the starting capacity of any locomotive is usually proportional to the weight on the drivers.

For passenger service, the higher tractive effort at starting gives the electric locomotive a great advantage, as a higher rate of acceleration can be obtained. Also for local passenger service the higher starting power makes it possible to maintain by electric operation a much higher schedule speed with frequent stops to

collect the passengers than could be done with the steam locomotive.

Competition for Different Classes of Railroad Service

The railroad traffic may be divided into six general classes:

1. Suburban passenger traffic.
2. Local or interurban passenger traffic.
3. Through passenger traffic.
4. Local or way freight traffic.
5. Through or drag freight traffic.
6. Manifest or time freight traffic.

The construction of electric trolley lines parallel to steam railroads in many parts of the country, and the operation of electric motor cars at frequent intervals, diverted nearly all of the first and second classes of traffic from the paralleling steam roads. As the trolley cars can accelerate more quickly than the steam trains, they can consequently maintain the same schedule speed and still make numerous stops for collecting passengers. The cost of operating the trolley lines ranges from 12 *to about* 22 *cents per car mile* for the one motor car trains, while it takes from 50 *cents to* $1.40 *per train mile* for steam operation. Consequently, the interurban electric lines can not only maintain a better service than the steam roads, but also they can afford to charge less fare than the steam railroads, and, as a result, they get nearly all the local passenger business and in addition create a new class of traffic. It has been demonstrated many times that an electric line will, on account of the better service it maintains, get a much larger local passenger traffic out of a territory than a steam railroad usually does.

At the present time the electric lines in many places are handling, with considerable success, a good deal of local freight business. The electric lines have not as yet materially affected that part of the revenue of steam roads which is obtained from the through passenger and freight traffic.

The experience with the electric locomotive has demonstrated its reliability. The operating cost data available from electrified steam railroads have made it evident that many steam railroads could now be operated more economically by electric power. However, the comparative economics of steam and electric railroad operation would, of course, have to be studied for each case, and to bring out the relative advantages and disadvantages of steam and electric operation of trunk line railroads a concrete example will now be discussed.

Description of Railroad Considered

Let us consider a single-track railroad constructed through a semi-arid region, similar to many parts of the West, which contains numerous irrigated and dry farm districts. The length of the railroad will be taken as 467 miles, and be divided into three engine districts, respectively 167, 160 and 140 miles long,

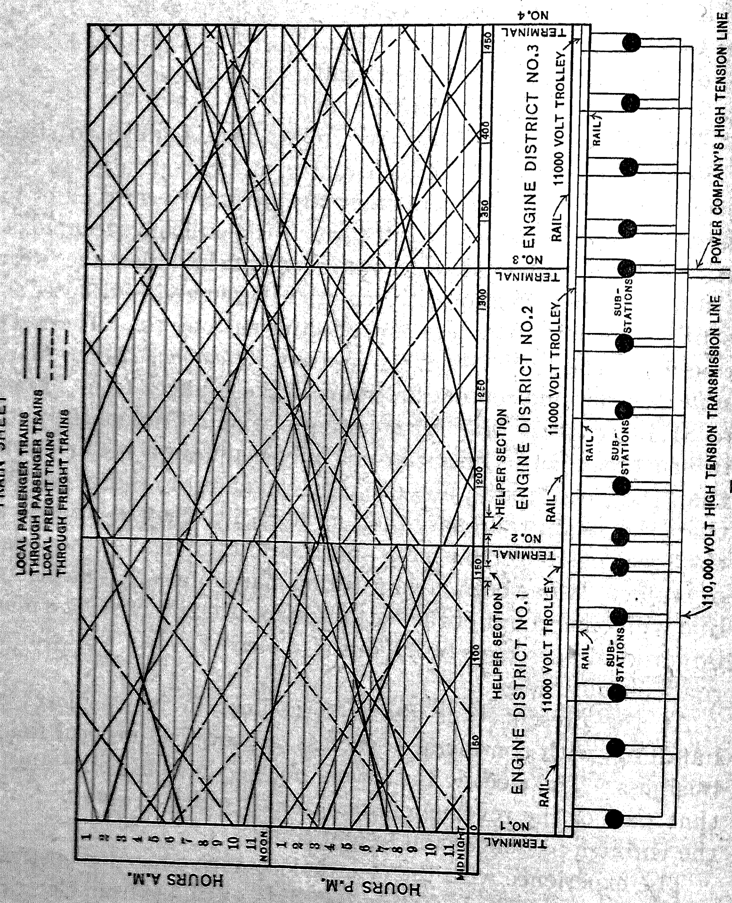


Fig 2

from the west towards the east, and will be referred to as engine district No. 1, No. 2 and No. 3, in the order named. The curvature averages about 12 degrees of central angle per mile and the ascents and descents of the grade average 18 feet per mile. The engine terminals will be referred to as terminal No. 1, terminal No. 2, terminal No. 3 and terminal No. 4, from west

towards the east. It will be assumed that there will be a helper district 9 miles in length for west-bound trains on engine district No. 1 and also one of the same length on engine district No. 2 for east-bound trains, the foot of these helper grades to be located 11 miles west of and 7 miles east of terminal No. 2 and the helper locomotives of both districts to be hostled and taken care of at terminal No. 2. The limiting grades of the three engine districts are shown in Table II. Also Table I and Fig. 2 will show the relative location of the engine districts and helper sections, together with other data of this railroad.

TABLE I

	Engine districts			Total
	No. 1	No. 2	No. 3	
Miles of main track	167.5	160	140.5	468
Miles of side track	54.5	51	50.5	156
Total main and side track	222	211	191	624
Miles curved track	35	33	32	100
Degrees of central angle per mile	12°	12°	12°	12°
Maximum curvature	6°	4°	4°	6°
Ascents and descents of grade per mile	14 ft.	22 ft.	18 ft.	18 ft.
Average grade	0.14%	0.21%	0.17%	0.17%
Weight of rail per yard	90 lbs.	90 lbs.	90 lbs.	90 lbs.

Steam Equipment. The through passenger trains to be handled by Pacific type locomotives of 192 tons weight with loaded tender, to handle from 5 to 14 coaches per train. The local passenger trains to consist of a 110-ton locomotive (with loaded tender) with a baggage car, smoking car and day coach, all cars being of 45 tons weight.

The freight trains to be handled by consolidated locomotives of total weight with coal and water of 185 tons and with 187,000 lb. on the drive wheels. The local freight trains to be handled by 130-ton locomotives.

Electric Operation. For comparison of steam and electric operation, the above line will be considered as equipped with an 11,000-volt, single-phase, 15-cycle trolley, with 110,000-volt, 15-cycle high-tension line to supply power to 14 substations. The power to be received into the high-tension system at terminal No. 3.

The local passenger trains to consist of two electric motor cars and one trailer. The through passenger trains to be hauled

by 100-ton electric locomotives. The local freight trains to hauled by an 85-ton locomotive, which class of locomotive also be used in switching service. The through freight tra (both expedite and drag) to be hauled by 110-ton locomotiv

Passenger Traffic. The passenger traffic to consist of through trains per day (three each way) over the whole ro On engine district No. 1 there will be four local passenger tra per day (two each way), while on engine districts Nos. 2 and there will only be two local passenger trains per day.

Freight Traffic. The annual freight traffic over each engi district will be assumed as follows:

Engine districts	Tonnage of cars and contents		
	No. 1	No. 2	No. 3
West bound:			
Expedite freight	800,000	700,000	800,000
Drag freight	1,700,000	1,700,000	1,600,000
Local freight	200,000	—	160,000
East bound:			
Expedite freight	600,000	600,000	600,000
Drag freight	1,300,000	1,300,000	1,200,000
Local freight	100,000	—	100,000

Number of Freight Trains

To determine the number of freight trains necessary to handl the above traffic, the maximum tonnage which the locomotive can haul over each engine district will have to be determined. Fo steam operation, this can be closely computed if the ruling an starting grades are known. Also a close approximation of th maximum tonnage by electric operation can be made if the aver age grades and their length are known, together with the maxi mum grades at starting.

However, the most accurate way of determining the maximum tonnage which can be hauled by a locomotive is to draw the veloc ity diagram for the limiting grade sections of the engine districts. Fig. 3 shows the profile and velocity diagrams for both steam and electric freight trains over the limiting grade sections of engine district No. 1. This will also give an idea of the variety of con ditions for which a locomotive of a trunk line railroad is used.

The limiting points are determined by the starting grades, the helper grades and the ruling grades. In computing the hauling

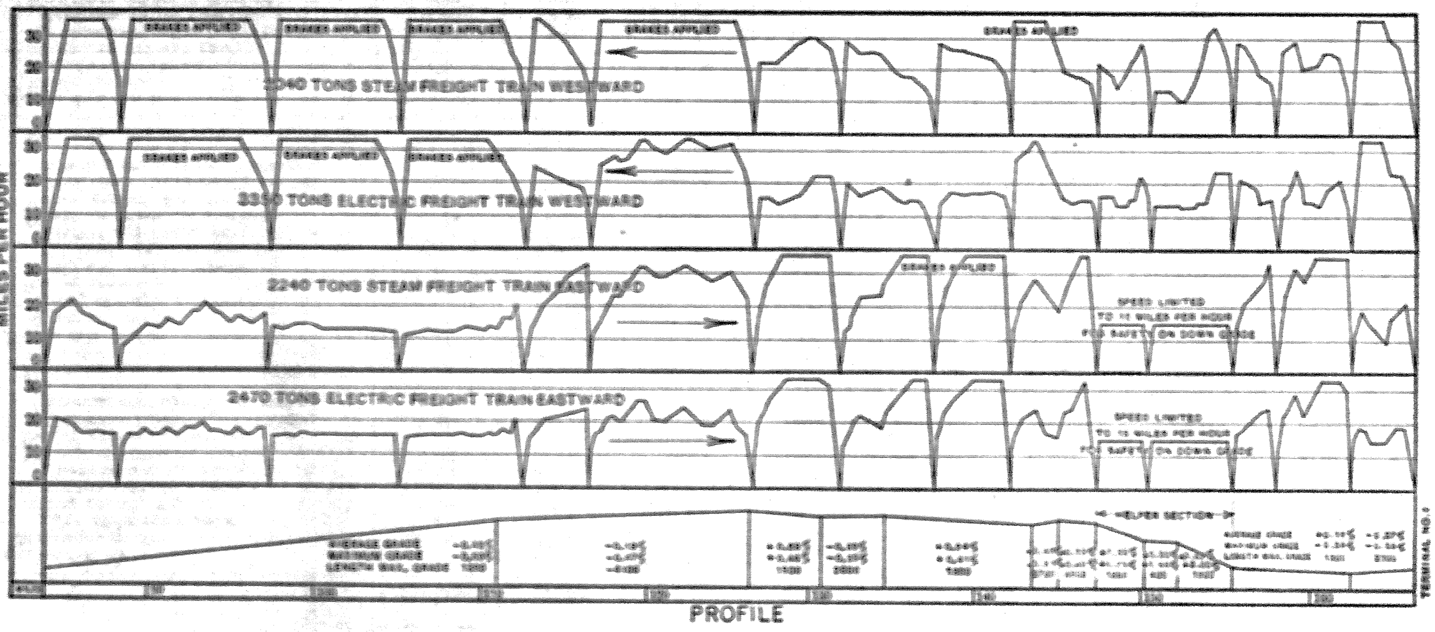


Fig 3 —Profile and Velocity Diagram of Freight Trains. (Part of First Engine District.)

TABLE II

	Limiting grades				Tonnage per train, including locomotive			
	West		East		Steam oper.		Electric oper.	
	Per cent	Length	Per cent	Length	West	East	West	East
Engine dist No. 1:								
Maximum grades (Exc. of helper grades)	0.56	600 ft.	0.6	1300 ft.	(Momentum Grades)			
Ruling grades (steam)	0.52	3800 ft.	0.55	2300 ft.	2350	2240	—	—
Maximum average grades.								
Continuous rating(electric)	0.22	21 mi.	0.45	28 mi.	—	—	3680	2470
Maximum grades at starting	0.32	—	0.46	—	2650	2240	3350	2780
Helper grades (3 engines):								
Maximum (momentary rating)	2.00	1900 ft.	—	—	2040*	—	3450*	—
Average grade(hourly rating)	1.3	8 mi.	—	—	—	—	4140*	—
Maximum tons per train actually hauled					2040	2240	3350	2470
Engine dist. No. 2:								
Maximum grades (Exc. of helper grades)	0.81	3100 ft.	1.00	3900 ft.	1690	1432	(Partly Momentum)	
Ruling grades (steam)	0.81	3100 ft.	1.0	3900 ft.	1690	1432	—	—
Maximum average grades:								
Continuous rating (electric)	0.3	8 mi.	0.48	28 mi.	—	—	(Partly Momentum)	2370
Momentary rating (electric)	0.81	3100 ft.	—	—	—	—	2590	—
Maximum grades at starting	0.29	—	0.5	—	2725	2150	3480	2750
Helper grades (2 engines):								
Maximum (momentary rating)	—	—	1.72	2300 ft.	—	1645*	—	2680*
Average grade (hourly rating)	—	—	1.11	9 mi.	—	—	—	3200*
Maximum tons per train actually hauled					1690	1432	2590	2370
Engine dist. No. 3:								
Maximum grades	0.88	1150 ft.	1.00	2.5 mi.	—	1432	—	—
Ruling grades (steam)	0.35	2 mi.	1.00	2.5 mi.	3000	1432	—	—
Maximum average grades:								
Continuous rating (electric)	—	—	0.55	17 mi.	—	—	—	2160
Moment. rating (electric)	0.35	2 mi.	—	—	—	—	4583	—
Maximum grades at starting	—	—	0.7	—	4300	1795	5500	2290
Maximum tons per train actually hauled					3000	1432	4583	2160

*Without weight of helper locomotives

capacity for steam locomotives, it is usual to make 10 miles per hour the minimum speed in order to allow for weather conditions, the personal equation of the engineer, and other variable conditions.

In Fig. 3 it will be noted that west, bound steam freigh ttrains of 2040 tons get down to 10 miles per hour at about mile post 152, on the helper section, and hence the helper section limits the weights of steam freight trains. The starting capacity of the steam locomotive is also nearly reached with the same tonnage. For west-bound electric trains, the starting grades limit the weight to 3350 tons.

The weight of east-bound steam freight trains is limited to 2240 tons by the ruling grade, 0.55 per cent. The starting grades also will not permit a heavier steam train. The weight of the east-bound electric freight trains (2470 tons) is limited by the long 21-mile grade from mile post 82 to mile post 111, which averages 0.45 per cent, the maximum grade in this distance being 0.6 per cent. It is on these long grades, where the electric locomotive operates on its continuous rating, that the steam locomotive compares most favorably with the electric locomotive. But even here the steam locomotive's hauling capacity is determined by the ruling grade, 0.55 per cent, which is very short, while the hauling capacity of the electric locomotive is determined by the average grade, 0.45 per cent.

In like manner, the weight of the freight trains was computed for engine districts Nos. 2 and 3. The maximum grade in most cases equals the ruling grade for steam operation. The maximum average grades, which govern the weight of the electric trains, are much lighter than the maximum grades; also the average grades are not of any great length and, consequently, the electric locomotive can exert considerably greater tractive effort than its continuous capacity. As a result, the electric locomotive can haul from 50 per cent to 60 per cent greater tonnage than the steam locomotive over these engine districts.

Table II shows the limiting grades of all engine districts, together with the maximum tonnage which can be handled by the 185-ton steam consolidated freight locomotive and the 110-ton electric freight locomotive, whose characteristics are shown in Fig. 1.

Table No. III gives the maximum trailing tonnage which the steam and electric freight locomotives can haul over the different engine districts:

TABLE III

TRAILING LOAD OF DRAG FREIGHT TRAINS IN TONS

	Steam locomotive		Electric locomotive	
	West	East	West	East
Engine district No. 1	1855	2055	3240	2360
Engine district No. 2	1505	1247	2480	2260
Engine district No. 3	2815	1247	4472	2050

The above trailing weights were obtained by subtracting the weights of the steam (185-ton) and electric (110-ton) locomotives from the total train weights given in Table II. The minimum speed of the electric freight trains is considerably greater than for steam freight trains, as it ranges from 14 to 16 miles per hour, which is high enough for expedite trains. The maximum steam train weights for expedite freight trains would have to be lighter than those given in Table III, as greater speed is required. Table IV gives the weights of the expedite trains:

TABLE IV

TRAILING LOAD OF EXPEDITE FREIGHT TRAINS IN TONS

	Steam locomotive		Electric locomotive	
	West	East	West	East
Engine district No. 1	1529	1697	3240	2360
Engine district No. 2	1235	1018	2480	2260
Engine district No. 3	2335	1018	4472	2050

In actual practise, the average weight of the trains would not be as great as given in Tables III and IV, since during slack times there are not always enough cars to load the engines to their maximum and, consequently, a number of short weight trains have to be operated. For the railroad considered, it will be assumed that the weight of the expedite and drag trains averages about 80 per cent of the maximum allowable weight or tonnage rating given in Tables III and IV. The number of local freight trains is generally governed by local conditions.

Table V shows the number of freight trains per year necessary to handle the freight traffic given above.

TABLE V
NUMBER OF FREIGHT TRAINS PER YEAR

	Steam locomotive			Electric locomotive		
	West	East	*Total	West	East	*Total
Engine dist. No 1:						
Expedite trains	656	442	1312	309	318	636
Drag trains	1149	793	2298	656	688	1376
Local trains	400	400	800	400	400	800
Totals			4410			2812
Engine dist. No. 2:						
Expedite trains	809	741	1618	404	335	808
Drag trains	1417	1300	2834	859	727	1718
Totals			4452			2526
Engine dist. No. 3:						
Expedite trains	428	741	1482	225	372	744
Drag trains	711	1200	2400	450	747	1494
Local trains	320	320	640	320	320	640
Totals			4522			2878

*As it is necessary to operate the same number of trains in both directions on account of train crews and equipment, the totals, of course, are twice the greatest number of trains required in one direction.

On all railroads the traffic at some seasons of the year is greater than at others. However, it is seldom that the passenger and freight busy seasons happen at the same time. The freight tonnage is generally greatest in agricultural districts after the crops are harvested, which is generally in the fall. The time of the greatest passenger traffic will depend on local conditions but, as stated above, seldom happens at the same time as the heavy freight movements. The writer has been often surprised at how uniform the train mileage and ton mileage per mile of line is during the year. For the railroad considered, the maximum and average number of trains per day is taken as follows:

TABLE VI
NUMBER OF TRAINS PER DAY—(BOTH WAYS)

	Eng. dist. No. 1		Eng. dist. No. 2		Eng. dist. No. 3	
	Average day	Maximum day	Average day	Maximum day	Average day	Maximum day
Steam trains:						
Passenger	10.0	10.0	8.0	8.0	8.0	8.0
Freight	12.1	16.0	12.2	17.0	12.4	18.0
Total	22.1	26.0	20.2	25.0	20.4	26.0
Electric trains:						
Passenger	10.0	10.0	8.0	8.0	8.0	8.0
Freight	7.7	11.0	6.9	10.0	7.9	12.0
Total	17.7	21.0	14.9	18.0	15.9	20.0

Table VII shows the train mileage, ton mileage, and locomotive mileage necessary to handle the assumed traffic over the railroad considered. The locomotive mileage includes the mileage to and from trains and the switching locomotive mileage.

TABLE VII

	Steam Operation	Electric Operation
Train miles:		
Local passenger trains	462,820	000
" motor trains	000	462,820
Through passenger trains	1,022,730	1,022,730
Total passenger	1,485,550	1,485,550
Local freight trains	233,200	233,200
Through "	1,858,670	953,344
Work trains	81,120	81,120
Total freight trains	2,172,990	1,267,664
Total all trains	3,658,540	2,753,214
Locomotive and motor car mileage:		
Motor car mileage	000	971,922
Passenger locomotives	1,559,828	1,073,867
Local freight locomotives	240,196	240,196
Through "	1,914,430	981,944
Work train	107,624	107,624
Helper locomotives	225,474	102,111
Switching	397,000*	*397,000
Total freight, work, helper and switch	2,884,724	1,828,875
Total locomotive mileage	4,444,552	2,902,742
Locomotive ton mileage:		
Motor cars	000	83,307,600
Passenger locomotives	259,638,174	107,386,700
Freight locomotives	385,395,130	129,631,480
Work train locomotives	15,067,360	9,686,160
Helper locomotives	41,712,690	8,386,510
Switching locomotives	55,880,000	35,730,000
Total freight, work, helper and switch	498,055,180	183,434,150
Total all locomotives and motor cars	757,693,354	374,128,450
Ton mileage—cars and contents:		
Passenger trains	744,424,800	675,001,800
Freight trains	2,113,300,000	1,940,045,780
Work trains	40,560,000	40,560,000
Switching	158,800,000	158,800,000
Total cars and contents	3,057,084,800	2,814,407,580
Grand total ton-miles	3,814,778,154	3,188,536,030

*Six miles allowed for each hour a switch engine is in service.

Number of Locomotives Required

An examination of the records of numerous steam railroads will disclose the fact that a steam locomotive spends a good portion of its time in the shops undergoing heavy repairs. Also that a larger part of its time is spent in or near the engine houses where the boiler washing is done, the fire boxes and flues cleaned, and the light running repairs are made, etc. The records of two western steam roads show that their passenger locomotives spent respectively 21 per cent and 17 per cent of their time in the shops, and that the freight locomotives of the same roads were in the shop 30 per cent and 24 per cent of their time.

The most complete record of the actual distribution of engine service I have seen is given in Table VIII, which is for a section of a railroad between 500 and 600 miles in length.

TABLE VIII

	Passenger locomotives		Freight locomotives	
	Per cent of total time	Days per year	Per cent of total time	Days per year
Time in shops	22.4	82	28.2	103
Time spare	1.4	5	2.7	10
Time in enginehouse (having running repairs done, boilers washed, fire boxes cleaned)	53.2	194	35.9	131
Time running to and from trains	1.6	6	1.1	4
Time in helper service	1.1	4	4.3	16
Time on road	20.3	74		
Actually running			17.1	62
Standing on sidings, taking water, etc.			10.7	39
Totals	100	365	100	365

It will be noted that each passenger locomotive was actually on the road, running or standing on sidings, only 74 days of the year, while each freight locomotive, exclusive of those used for helper service, was actually running only 62 days of the year and standing on sidings, etc., 39 days, not considering the helper locomotives.

The number of locomotives required to handle the traffic of any railroad depends of course upon the quantity of traffic, number of trains, the arrangement of the train schedule, ratio of maximum and average traffic, etc. An estimate of the number of

steam locomotives required to handle the trains over the road can be made from the train sheets, and to this number will have to be added an allowance to cover time in engine house, shops, etc. as shown above in Table VIII. However, the total number of steam locomotives shown in Tables IX, X, XI and XII, as required for operating the railroad discussed in this paper, is the

TABLE IX
PASSENGER SERVICE

	Steam locomotives			Electric locomotives		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shops	22.1	81	6.2	19.2	70	2.5
Spare	1.4	5	0.4	3.1	11	0.4
In enginehouse, etc.	53.0	193	14.8	27.7	101	3.6
Running to and from trains	1.6	6	0.5	3.8	14	0.5
In helper service	1.5	5	0.4	3.1	11	0.4
On road	20.4	75	5.7	43.1	158	5.6
Totals	100	365	28	100	365	13

TABLE X
FREIGHT SERVICE

	Steam locomotives			Electric locomotives		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shop	28.0	102	26.9	25.1	91	10.8
Spare	2.7	10	2.6	6.0	22	2.6
In engine house	35.8	131	34.4	27.9	102	12.0
Running to and from trains	1.1	4	1.1	1.4	5	0.6
In helper service	4.8	17	4.6	3.5	13	1.5
Standing on sidings	10.6	39	10.1	13.7	50	5.9
Running on road	17.0	62	16.3	22.4	82	9.6
Totals	100.0	365	96.0	100.0	365	43.0

same as that actually used on a western railroad where the quantity of traffic and other conditions are similar. The number of electric locomotives given was estimated from the steam figures.

As there would be the same number of passenger trains, the number of passenger locomotives required (assuming all trains to

be locomotive trains, on the road would be the same for both steam and electric operation, except that, as no time would be used in taking water, a smaller number of electric locomotives would be needed on the road than by steam operation. There would be fewer freight trains by electric operation and, consequently, fewer electric freight locomotives would be needed than steam freight locomotives, in addition to the smaller number of electric locomotives required on account of not having to take water.

TABLE XI
SWITCHING SERVICE

	Steam locomotives			Electric locomotives		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shops	[illegible]	[illegible]	6	[illegible]	22	[illegible]
In service	[illegible]	224	[illegible]	[illegible]	[illegible]	8
Totals	100.0	365	36	100.0	365	[illegible]

TABLE XII
SUMMARY

	Steam Equipment	Electric Equipment
Passenger service		
Motor cars	0	14
Passenger locomotives	58	[illegible]
Freight locomotives	56	41
Switching locomotives	36	[illegible]
Total motor cars	0	14
Total locomotives	150	64

The time in the engine house, where the inspection, cleaning and light repair work is done, will manifestly be much less with electric than with steam locomotives. A steam locomotive receives a thorough inspection after each run, whereas the practice with electric locomotives is to inspect them after they have made a certain mileage, which varies from 1200 to 2500 miles, the former figure being the New York Central standard, while the latter is the practice of the Pennsylvania Railroad at New York.

The boiler washing, fire box cleaning and other things required on a steam locomotive, and which consume a large part of the

time in the engine house, would not be necessary with electric locomotives and, consequently, the time spent by electric locomotives in or near the engine house would be much less than with steam locomotives. Likewise, electric locomotives would spend less time in the shops than steam locomotives, as there would be no boiler, firebox, smoke stack or tender to repair.

The above remarks, supplemented by Tables IX to XII inclusive, show how the number of electric locomotives needed to handle the given traffic was estimated.

Tables IX and XII show the number of locomotives and distribution of engine service for steam and electric operation of the 467-mile railroad being discussed.

Thus 13 passenger locomotives would be needed if all passenger trains were locomotive trains, but as electric motor cars are to be used for local passenger trains, only 10 electric locomotives would be needed for the through passenger trains, in place of 13 as shown in Table IX, but 14 motor cars would also be needed for the local passenger trains.

As a check on the above figures for number of locomotives required some data will now be given of electrified steam lines in operation. Table XIII below was computed and condensed from data given in a paper by Mr. W. J. Wilgus, Volume 61, A.S.C.E., concerning the electric operation of the N.Y.C. & H.R.R.R., and which, as I understand it, shows the distribution of steam and electric locomotive time out of the shop.

TABLE XIII

	Hours		Per cent	
	Steam locomotives	Electric locomotives	Steam locomotives	Electric locomotives
Busy	138.00	203.92	20.7	30.3
Waiting	174.10	229.19	26.2	34.2
Total	312.10	433.11	46.9	64.5
Dead	354.90	238.89	53.1	35.5
Grand total	667.00	672.00	100.0	100.0

These data, which are for all classes of locomotives, would indicate that for conditions on the New York Central the steam locomotives were having fire boxes cleaned, boilers washed,

light repairs made, and other things which are done in the engine house, a little over half the time out of the shops, while the time spent by the electric locomotives in the engine house being inspected, having light repairs made, etc., was only about one third of the time out of the shops.

Conditions on different roads are of course not the same, but I believe Table XIII shows that the estimates of number of electric locomotives for the 467-mile railroad here considered, given in Tables IX to XII inclusive, are very conservative in most items.

Estimated Cost of Electrification

The following is an estimate of the money needed to electrify the 467 miles of steam railroad considered:

High-tension lines (*steel tower*), 450 *miles*		$2,250,000
Trolley and feeder wire:		
3/0 grooved copper trolley, 468 mi. at $650	304,200	
Steel trolley wire, 156 mi., at $320	49,920	
2/0 feeder wire, 468 mi. at $500	234,000	
		588,120
Overhead construction:		
Bracket arm construction, 420 mi. at $1650	$693,000	
Span construction, 92 mi. at $2600	239,200	
Steel bridges, 4 mi	36,000	
Section breaks	6,600	
Additional for curved track, 100 mi. at $300	30,000	
		1,004,800
Track bonding:		
624 mi. at $450		280,800
Substations:		
14 substations, 56,000 kv-a.	$616,000	
3 portable stations, 6000 kv-a. (complete)	96,000	
		712,000
Rolling stock:		
14 motor cars, $18,000	$252,000	
10 passenger locomotives, $45,000	450,000	
43 freight locomotives, $50,000	2,150,000	
11 switching locomotives, $35,000	385,000	
		3,237,000
Changing block signals and telegraph (468 *mi.*)		561,600
Engineering and supervision, 5 per cent		431,716
Contingencies, etc., 10 per cent		905,964
Total		$9,972,000
Credit for steam equipment:		
140 locomotives	$2,520,000	
241 coal cars	241,000	
14 passenger cars	112,000	
Give credit for, say, about 70 per cent of new value	2,873,000	2,012,000
Net estimate		$7,960,000

The figures given apply to the intermountain regions of the West. As the actual construction cost was available of a high-tension steel tower line parallel to a railroad, the material being distributed by work trains of the railroad, the estimate for this item given should be very close. The trolley line and substation estimates were based upon interurban construction cost of two lines in the West, a liberal allowance being made for the heavier work needed for trunk lines. No item is shown for electric shop machinery, as credit for steam locomotive shop machinery will offset this expense.

Comparative Cost of Maintenance and Operation by Steam and Electric Power

Having determined the amount of traffic of the railroad, and the number of trains necessary to handle it by steam and electric locomotives, the comparative cost of operation by steam and electric power will now be given.

While the bookkeeping methods are different on different railroads, the items into which the various maintenance and operating expenses are divided are the same, as the instructions of the Interstate Commerce Commission are followed. There are six general subdivisions into which the maintenance and operation expenses of a railroad are divided, as follows:

I. Maintenance of Way and Structures.
II. Maintenance of Equipment.
III. Traffic Expenses.
IV. Transportation Expenses.
V. General Expenses.
VI. Taxes.

The above headings are subdivided into numerous accounts. Traffic and General Expenses would not be affected by the kind of motive power and they will not be considered. For convenience in making the comparison between the steam and electric operating costs, the first heading will be divided into three parts and the second into two parts. The general headings will then be as follows:

A. Maintenance of Way and Structures.
B. Maintenance of Overhead Structures and Substations.
C. Depreciation of Overhead Structures and Substations.
D. Maintenance of Equipment.
E. Depreciation of Equipment.
F. Transportation Expenses.
G. Taxes.

The above headings are subdivided, as shown below, into 50 items or accounts. Tables XIV to XX below give the comparative steam and electric operating expenses of the 467-mile railroad considered.

TABLE XIV

MAINTENANCE OF WAY AND STRUCTURES

	Steam	Electric	Steam	Electric
	Per cent	Per cent		
1. Ties	100	92.5	$163,800	$151,515
2. Applying ties	100	92.5	46,800	43,290
3. Rail and other track material	100	85.0	93,600	79,560
4. Applying rail and other track material	100	85.0	32,760	27,846
5. Maintenance and care of track	100	95.0	234,000	222,300
6. Maintenance and care of roadbed	100	100.0	74,880	74,880
7. Signals	100	75.0	22,400	16,800
8. Telegraph	100	100.0	13,680	14,040
9. Engine house and shops	100	50.0	23,400	11,700
10. Fuel and water stations	100	[illegible]	23,400	[illegible]
11. Roadway tools and supplies	100	92.5	23,400	21,645
Totals			$[illegible]	$[illegible]

TABLE XV

MAINTENANCE OF OVERHEAD STRUCTURES AND SUBSTATIONS

	Steam operation	Electric operation
12. *Maintenance of trolley line*		
Bracket construction, 420 mi. at $100	000	$42,000
Span construction, 92 mi. at $120	000	11,040
Steel bridges, 4 mi. at $60	000	240
13. Maintenance of high-tension line, 450 mi. at $50	000	22,500
14. Maintenance and inspection of substations	000	7,450
15. Track bonding, 624 mi. at $20	000	12,480
Totals	000	$95,710

TABLE XVI

DEPRECIATION OF OVERHEAD STRUCTURES AND SUBSTATIONS

	Steam operation	Electric operation
16. *Trolley wire:*		
Copper, $304,200 at 4 per cent	000	$12,168
Steel trolley, $40,920 at 5 per cent	000	2,046
17. Feeder wire, $234,000 at 1 per cent	000	2,340
18. Poles and fixtures, $968,000 at 5 per cent	000	48,400
19. Steel bridges, $36,000 at 3 per cent	000	1,080
20. Track bonding, $281,000 at 4 per cent	000	11,240
21. High-tension line, including copper, $2,250,000 at 2 per cent	000	45,000
22. Substations, $712,000 at 3 per cent	000	21,360
Totals	000	$144,084

TABLE XVII

MAINTENANCE OF EQUIPMENT

	Steam operation	Electric operation
23. *Passenger locomotive repairs:*		
Steam, 1,559,828 miles at 10c.	$155,983	
Electric, 1,073,867 miles at 4½c.		$48,324
24. *Freight and switching locomotive repairs:*		
Steam, 2,884,724 miles at 14c.	403,861	
Electric, 1,828,875 miles at 6c.		109,732
25. *Electric motor car repairs:*		
Electric, 971,922 miles at 3c.	000	29,158
26. *Passenger car repairs:*		
Steam, 13,661,220 mi. at 1.2c.	163,935	
Electric, 12,735,580 mi. at 1.2c.		152,827
27. *Freight car repairs:*		
46,500,000 car miles, at 0.6c.	279,000	279,000
28. *Coal cars (company coal):*		
3,850,000 car miles at 0.6c.	23,100	000
Totals.	$1,025,879	$619,041

TABLE XVIII

DEPRECIATION OF EQUIPMENT

	Steam operation	Electric operation
29. Depreciation of locomotives, (steam, 3 per cent)	$75,600	
(electric, 2 per cent)		$59,700
30. Depreciation of motor cars, 2 per cent.	000	5,040
31. Depreciation passenger cars released, 3 per cent.	3,360	000
32. Depreciation coal cars released, 3 per cent.	7,230	000
Totals.	$86,190	$64,740

The steam operating expenses given in Tables XIV to XX are based upon actual steam railroad operation and the following remarks will show how the electric operating expenses were computed.

Ties. A comparison of the tie renewal cost of different railroads with different tonnage, at first glance, may seem to show no relation between tie renewals and ton mileage per mile of line. However, a careful study will show that upon railroads of light tonnage the tie renewals depend more upon how long the tie will last without rotting, while upon railroads of very heavy tonnage, it will be found that the ton mileage per mile of line is the most important factor in the tie renewals. The exact amount of tonnage which will cause the tie to wear out before it has rotted depends upon the character of the soil, kind of tie, whether treated or

TABLE XIX

TRANSPORTATION EXPENSES

	Steam operation	Electric operation
33. *Engine and motormen on switching locomotives:*		
Electric, 70 per cent of steam	$50,000	$35,000
34. *Engine and motormen on passenger locomotives:*		
Steam, 1,559,828 miles at 8c	124,786	
Electric, 1,073,867 miles at 8 c		85,909
35. *Engine and motormen on freight and work locomotives:*		
Steam, 2,262,250 miles at 11c	248,848	
Electric, 1,329,764 miles at 11c		146,275
36. *Enginemen and motormen on helper locomotives:*		
Steam, 225,475 miles at 12c	27,056	
Electric, 76,241 miles at 12c		9,149
37. *Car motormen:*		
462,820 miles at 2c	000	9,256
38. *Conductors and brakemen in switching service*	90,000	90,000
39. *Passenger locomotive train crews:*		
Steam, 1,485,550 miles at 6.8c	101,017	
Electric, 1,022,730 miles at 6.8c		69,546
40. *Motor car trainmen:*		
462,820 miles at 4c	000	18,513
41. *Freight and work train crews:*		
Steam, 2,262,250 train miles at 13c	294,093	
Electric, 1,328,764 train miles at 13c		172,739
42. *Fuel:*		
400,000 tons at $2.25	900,000	000
43. *Purchase of power:*		
90,000,000 kw-hr. at 0.75c	000	675,000
44. *Water*	52,000	000
45. *Lubricants*	14,000	6,000
46. *Other locomotive supplies*	23,000	16,100
47. *Engine house expenses, locomotives:*		
Steam, 40,000 locomotives at $2.50	100,000	
Electric, 14,000 locomotives at 80c		11,200
48. *Engine house expense, motor cars:*		
3,000 motor cars at 50c	000	1,500
49. *Signal operation*	40,000	35,000
Totals	$2,064,800	$1,381,187

TABLE XX

SUMMARY—OPERATING EXPENSES

	Steam operation	Electric operation
A. Maintenance of way and structures	$671,540	$572,096
B. Maintenance of overhead structures and substations	000	95,710
C. Depreciation of overhead structures and substations	000	144,084
D. Maintenance of equipment	1,025,879	619,041
E. Depreciation of equipment	86,190	64,740
F. Transportation expense	2,064,800	1,381,187
G. Taxes		31,551
Totals	$3,848,409	$2,908,409

Steam operation expenses	$3,848,409
Electric operation expenses	2,908,409
Annual saving effected by substitution of electric power	$940,000

and a number of other varying quantities, and therefore cannot be definitely determined for all conditions. In the above it was assumed that 50 per cent of the tie renewals was proportional to the ton mileage per mile of line, while the other 50 per cent is not affected by the tonnage. As the electric ton mileage is 85 per cent of the steam ton mileage, the estimated electric tie renewal cost was (85 per cent × 50 per cent + 50 per cent) = 92.5 per cent of the steam tie renewal cost.

Rails and Track Maintenance. Experience has shown that the wear on the rails, fastenings and other track material, as well as the cost of the maintenance and care of the track varies according to the traffic handled over the road. Steam locomotives, on account of the greater weight on the drivers, have been found to cause more damage to the track per ton than the cars. As there is less ton mileage per mile of line by electric operation than by steam, on account of the electric locomotives being lighter and fewer being necessary, as fewer and heavier trains are operated, it is reasonable to expect that the damage to the track will be much less by electric operation than by steam operation. It has been definitely shown in steam operation that if a larger steam locomotive is continuously operated on a division, additional labor will be required on the track of that division. The cost of rail and other track material and the maintenance and care of the track in above estimates was assumed to be directly proportional to the ton mileage. The greater damage per ton by the locomotive was ignored, as it was desired to make a conservative estimate.

Maintenance and Care of Roadbed. This account includes such items as drains, ditches, sloping cuts, removing slides, cutting weeds, protection of the roadbed from water, etc., and will not be affected by electric operation. It is included in the above and is considered here in order that it will not be confused with any track maintenance.

Signals and Telegraph. The cost of the signal system maintenance which by steam operation is operated by storage batteries would be considerably reduced, as no battery expense would be necessary, while on the other hand the telegraph line and signal wires would cost more, on account of the interference of the trolley and high-tension line circuits.

Engine Houses and Shops. This expense will be much reduced by electric operation, both because there will be no smoke and gases to contend with and because fewer electric locomotives will be handled.

Locomotive Fuel and Water Stations. These items will, of course, not be necessary for electric operation. However, if water-cooled transformers are used, a portion of the water station expense will be necessary.

Roadway Tools and Supplies. Half of this item is assumed to be independent of electrification, the other half is assumed to vary as the ton mileage, as the track maintenance expenses will be greater if the traffic is greater, and by electric operation the ton mileage would be less than by steam operation.

Maintenance of Overhead Structures. The typical arrangement of the overhead structures proposed, where there are no yards, is to have high-tension steel tower line paralleling the track and the bracket arm type of trolley construction, with wood poles and one feeder wire. The figure of $150.00 per mile used to cover the maintenance and inspection was based upon the present cost of steel tower, wood pole and interurban trolley line maintenance in this western section, an allowance being made for the more expensive maintenance cost of the heavier construction needed on a trunk line railroad. The same men are to be used to look after both the high-tension and trolley lines. The figures given above for the span and steel bridge construction were estimated in like manner.

Maintenance of Substations. No attendants were considered necessary, as it is assumed that the inspection and light maintenance could be done by the linemen. In case of accident, the trouble department would take hold, as is now done by the wrecking crew on steam railroads, portable substations being provided in case of a complete shut-down.

Depreciation of Overhead Structures and Substations. In addition to the maintenance of the overhead structures and substations there is also the depreciation and renewal expense, and Table XVI shows the percentage used in this estimate.

Locomotive Repairs. Experience has shown that the repair expense of an electric locomotive is much less than that of a steam locomotive, which should be the case, as there is no boiler, firebox, smoke stack or tender on an electric locomotive, as has been stated before.

Also, there are operating factors entering into the repair cost which should be considered. Table XXI below gives some cost data of a Western railroad, which will be useful in showing the effect of different operating factors on the repair expense.

TABLE XXI

Class of locomotive	Total weight with loaded tender (tons)	Weight on drivers pounds	Average number of locomotives	Number of years record	Miles per year per locomotive	Annual repair cost of each locomotive	Repair cost per locomotive mile
Passenger locomotives, Atlantic type	165	105,000	11	8 yrs.	60,500	$4200	6.95c
Passenger locomotives, Pacific type.	192	141,000	7	8 yrs.	65,100	5550	8.52c
Freight locomotive Consolidated simple type..........	159	178,000	5	9 yrs.	23,500	2500	10.67c
Freight locomotive consolidated simple type..........	185	187,000	63	5 yrs.	30,300	3845	12.69c
Helper locomotive Consolidated compound type.......	155	165,300	15	6 yrs.	14,500	2785	19.21c
Switch locomotive 10-wheel type......	110	140,000	13	9 yrs.	In service 4750 hours per yr.	1950	——

The above figures are averages of several years, but since the cost of both labor and material has greatly increased during the last few years, the averages shown are somewhat less than what the actual cost now is. The annual repair cost of the high-speed steam passenger locomotives is shown above to be much higher than the low-speed freight locomotives, but the locomotive-miles per year of the passenger locomotives is so much greater than the annual mileage of the freight locomotives that the cost per locomotive-mile—which is really a measure of the cost of train operation—is considerably less for the passenger locomotives. It will also be noted that the repair cost seems also to vary with the weight of the locomotive, and especially the weight on the drive wheels.

The high cost shown for the helper locomotives resulted from three causes. The annual mileage was very low. The engines were used on the maximum grades and consequently when ascending these grades were stressed to their maximum and also required full braking when descending these heavy grades. The more complicated mechanism of compound engines is also more expensive to maintain than that on simple engines.

Thus the cost of locomotive repairs varies according to kind

of service, class of engine, grades, mileage, etc. A study of the repair cost details shows that they are in many cases affected by local conditions. Thus the kind of water available, especially in some sections of the West, where considerable alkali water is present, may cause the boiler maintenance expense to become very large. The following is an estimate of the relative repair cost of steam and electric locomotives for the road considered, it being assumed that only a small amount of alkali water is used in the locomotives.

	Locomotive repair expense	
	Steam	Electric
	Per cent	Per cent
Boiler, firebox, tender, smoke stack	38	0
Running gear and machinery	62	45
Total	100	45

The steam locomotive percentages segregated above were estimated from a study of the details of the repair expense of one railroad with conditions similar to the road here considered. The method of keeping the records made it impossible to get an absolute segregation of the costs, but I believe the above is a fair estimate. The electric locomotive percentages were estimated from the steam records. The running gear repair expense was considered the same for both locomotives. The maintenance expense of the control apparatus and electrical equipment is not high on most modern electric locomotives, and it is reasonable to expect it to be less than the steam machinery costs, and it was considered so in the above estimated segregation. The painting and other miscellaneous expenses will not be any greater with an electric locomotive and probably will be a little less. The final results consider the electric locomotive repair expense to be only 45 per cent of the steam locomotive repair expense for the road here considered. The reliability of this estimate will now be checked by giving some actual figures of the relative repair cost of steam and electric locomotives.

The published figures of the N.Y.C. & H.R.R.R. (Vol.61, A.S.C.E.) show that the steam locomotives cost $1842.00 for repair during 335 days, while the electric locomotives only cost, during 350 days, for the same service, $704.00. The electric locomotive repair cost on the N.Y.C. & H.R.R.R. is thus only 36.5 per cent of the steam locomotive repair cost. Another

set of published figures gives for 1908 the cost per locomotive-mile as 2.83 cents for New York Central electric locomotives, and between 26,000 and 27,000 locomotive-miles as the annual mileage of 35 locomotives. The Interstate Commerce Commission records for 1908 show 8.2 cents per locomotive mile for all steam engines of the N.Y.C. & H.R., with annual mileage of 28,950 per locomotive, the annual passenger locomotive mileage being 38,400 and the annual freight locomotive mileage being 21,600 per locomotive. The cost per locomotive-mile segregated between passenger and freight service was not given. The 1912 New York Central electric locomotive repair cost published is 3.34 cents per locomotive-mile.

The figures published by Mr. Gibbs of the Pennsylvania R.R. give the electric locomotive repair cost as 5.91 cents per locomotive-mile, the New Jersey Division steam locomotive repair cost as 8.83 cents per locomotive mile, and the average of steam locomotives for all divisions of the Pennsylvania as 11.9 cents per locomotive-mile. The electric locomotive repair expense is thus only 67 per cent of the steam expense on the New Jersey Division and only 50 per cent of the steam repair expense on all divisions. The annual mileage of the electric locomotives was 26,000, 28 per cent of which was switching. The steam mileage is not given, but from Interstate Commerce Commission reports for 1910 it is shown as 27,610 for the whole road.

The extremely heavy grades on the electrified section of the Pennsylvania railroad of course make the repair cost of the electric locomotives considerably higher than if they were operated over a section with the grades as low as the average of the whole road, and consequently the relative cost of steam and electric locomotive repairs will be even less than shown. The electric locomotives of the P. R.R. are also much more powerful than the steam locomotives.

All things considered, it is probable that the electric locomotive repair cost will be even lower than 45 per cent of the steam locomotive repair cost, which was estimated above for the road considered, and used in making the comparative estimate of steam and electric operating expenses. For the road considered, the repair expense for steam passenger locomotives was taken at 10 cents per locomotive-mile, and steam freight, helper and switching locomotives 14 cents per locomotive-mile, which figures were based on the present locomotive repair costs on a Western railroad where similar conditions exist. The electric locomotive repair

expense will thus be 4.5 cents per locomotive-mile for passenger locomotives and 6 cents per locomotive-mile for freight service. The helper locomotives are more expensive to maintain than road engines, but, on the other hand, the switching locomotives cost less. The freight, helper and switching locomotives were combined in order to simplify computations.

Electric Motor Car Repairs. There are numerous data available on the repair cost of motor cars and 3 cents per car-mile, exclusive of inspection, which is included under the head of engine-house expenses, was used in the above estimate.

Passenger and Freight Car Repairs. These items will decrease by electric operation, as some passenger cars would be released by the use of electric motor cars, and in like manner the freight car repairs account is decreased by electric operation on account of no coal cars being used for hauling locomotive coal, as power is purchased.

Depreciation of Locomotives. An electric locomotive will have a longer life than a steam locomotive, and thus the rate of depreciation will be less. However, the electric locomotive usually costs so much more than a steam locomotive that the actual depreciation charge per locomotive is generally greater in the case of the electric locomotive. On the other hand, the number of steam locomotives required to handle a given traffic is in most cases much greater than the number of electric locomotives required and, consequently, the total depreciation is generally greater for steam operation. The statement below shows the depreciation percentages used in the above tables. The steam locomotive figures were obtained from the auditing department of a western line. The electric figures were estimated, and although the modern electric locomotive has been in use only half the time allowed below for its life, I think past experience justifies the expectation of the life allowed. In any case, I do not believe there is any question as to the relative life of steam and electric locomotives.

	Steam locomotive	Electric locomotive
	Per cent	Per cent
First cost of locomotive	100	100
Salvage value when worn out	20	30
Total cost	80	70
Estimated life	26⅔ yr.	35 yr.
Annual depreciation	3%	2%

Depreciation of Passenger and Freight Cars. The following statement shows the methods used and the percentages estimated for these items:

	Passenger cars	Steel freight cars
	Per cent	Per cent
First cost	100	100
Salvage value	15	20
Total cost	85	80
Estimated life	$28\frac{1}{3}$ yr.	$26\frac{2}{3}$ yr.
Annual depreciation	3%	3%

Enginemen and Motormen. The wages of the motormen on the electric locomotives were assumed to be the same as those of the enginemen on the steam locomotive, but the motormen on the electric motor cars were taken as equal to about what would be paid for trolley car service. Although no fireman is needed on electric locomotives, two men were assumed necessary for all electric road and helper locomotives; but on switching locomotives, which have a conductor, and sometimes two or three switchmen, only a motorman was allowed. When two electric locomotives are used on a helper district to assist the road locomotive, only one crew was allowed, as the electric helper locomotives, being equipped with multiple-unit control, can be operated by one crew.

Trainmen. The reduction in this item is caused by operating fewer freight trains and in the case of the motor car trains a smaller train crew will be required than in the case of a steam train.

Fuel Expense. All coal used on a steam locomotive is not utilized in hauling trains but a good deal is wasted by radiation while the locomotive is standing on sidings, imperfect combustion in the firebox, starting fire, etc., and the loss of energy is very much greater than would be the case in a steam-electric plant generating power for electric operation of a railroad. The figures published by Mr. W. S. Murray in a discussion* in November, 1907, indicate that it requires about double the coal for operation of the steam locomotives of the N. Y. N. H. & H. R.R. that it does to generate power in a steam-electric power plant for operation of its electric locomotives in the same service.

There are few railroads where coal is obtained for less than from \$2.00 to \$2.25 per ton and some pay more than double the high-

*TRANS. A. I. E. E., Vol. XXVI, 1907, p. 1680.

est figure mentioned. For the road here considered, coal will be estimated to cost $2.25 per ton and be delivered at terminal No. 4.

The quantity of coal is the same as the actual amount used on a steam railroad for all classes of service where conditions are similar to those here discussed.

The hauling of the locomotive coal over the railroad's own line is a very important item, as it amounts to 174,000,000 ton-miles, as it was assumed to be delivered to the railroad at terminal No. 4 at the east end of the line. In this connection, attention should be called to the fact that if some section of the railroad toward the west was considered for electrification, the cost of hauling the coal over the other portion of the line should properly be considered in connection with electrification estimates. For the case here considered, the cost of hauling the coal is taken care of by allowing fewer train-miles, fewer locomotive-miles and fewer ton-miles, in the figures given for electric operation.

Electric Power. The quantity of electric power needed was computed from the grades, train weights, speed and other necessary data. The average power for a train of two motor cars and trailer, making stops every six or eight miles, was taken at 40 watt-hours per ton-mile. The passenger locomotive trains were allowed 31 watt-hours per ton-mile. The freight trains were allowed 25 watt-hours per ton-mile and the switching locomotives were allowed 45 watt-hours per ton-mile.

As stated above, the power is to be purchased and delivered into the railroad's high-tension transmission line at terminal No. 3. The rate to be paid for electric power in any locality depends upon the local conditions, the load factor, cost of coal, etc.

The load factor on most of the present electrically operated railroads is generally very low. This will not be the case when the long trunk lines of railroad are electrically operated, as the heavy through passenger and freight trains operate night and day, and although there will be peaks in the load curve, I am inclined to believe that the power required to operate the railroad during different times of the day or year will be surprisingly uniform.

As an example, take the railroad considered: The greatest number of trains upon the line at one time on the maximum day of the year would be four motor car passenger trains, five through passenger trains and 18 freight trains. Some of these would be operating against grades and others would be running down grades. The maximum power on five-minute peaks for operating these trains should not exceed about 20,000 horse power. The average

load for the year would be 13,700 horse power. Considering the annual load factor equal to the ratio of the average load of the year to the maximum five-minute peak, the annual load factor for the above railroad would thus amount to 68.5 per cent. Allowing for emergencies and delayed trains, the load factor should not get lower than 60 per cent.

On the basis of coal at $2.25 per ton and a load factor of 60 per cent, there should not be much trouble in purchasing electric power at 0.75 cent per kw-hr., which figure was used in above estimates. However, at most points, a very high grade of coal is required for use on the locomotives, whereas a steam-electric plant can be designed so that slack or any of the low-cost grades of coal could be used. In the intermountain section of the West, the cost of slack coal is less than half that of run-of-mine coal, which is used for locomotives, and in a steam plant slack coal is nearly as efficient as run-of-mine coal.

In many sections of the West, the development of numerous hydroelectric plants at extremely low construction cost has made it possible to obtain power at some points at considerably lower cost than 0.75 cent per kw-hr., which was used in the above estimate. For instance, the Great Falls Power Company has made a rate of 0.536 cent per kw-hr. to the Chicago, Milwaukee & Puget Sound Railway, and agrees to construct some of the high-tension lines.

Engine House Expenses. The steam engine house expenses would be very much reduced if the road were electrically operated, for two reasons. There would be fewer inspections necessary with electric locomotives, and the nature of the engine house work is such as to require much less expense with electric locomotives, as there is no boiler washing, firebox cleaning, ash pit expense, etc., with electric locomotives.

It is customary to clean the firebox and give the steam locomotive a thorough inspection after each run, although boiler washing is only done after two or three runs, depending upon the quality of the water obtained. The practise with electric locomotives is to give them an inspection after a certain mileage, which ranges from 1200 to 2500 miles on different roads, as explained before. For the road here discussed, an allowance was made for an inspection of the electric locomotives after every round trip, which would mean an inspection after the locomotive had made a little over 300 miles. Possibly this allows too high an expense for the electric locomotive, but the estimates will be conservative.

It would be necessary to handle through the engine house at the terminals annually about 40,000 steam locomotives, or 14,000 electric locomotives, which in both cases contains an allowance for contingencies which always happen. Fewer electric locomotives are handled also because there are fewer electric than steam trains.

The cost per steam engine handled varies according to local conditions and other things. In the above estimates $2.50 per steam engine handled was allowed, which is based on actual operation costs where conditions are similar to the road discussed. The details of this, together with the estimated cost of handling electric locomotives, are shown in Table XXII below.

TABLE XXII

ENGINE HOUSE EXPENSES

	Steam locomotives	Electric locomotives
	Per cent	Per cent
Engine house foreman	1.3	1.3
Electric inspectors	0.0	2.0
Hostlers and helpers	7.0	6.0
Engine crew callers	2.3	2.3
Wiping and cleaning	16.7	11.7
Boiler washout	42.2	0.0
Cleaning flues	3.6	0.0
Stack inspectors	1.0	0.0
Supply men	2.7	2.7
Firing up engines	2.8	0.0
Sanding engines	1.3	1.2
Turntable (hand)	5.4	5.1
Sweeping engine house	1.2	1.0
Fueling engines	2.4	0.0
Cleaning fire boxes, etc.	5.4	0.0
Cleaning ash pits	4.7	0.0
Totals	100.0	33.3

Thus it is estimated that it only costs one-third as much to handle an electric locomotive through the engine house as it takes to handle a steam locomotive. At $2.50 per locomotive for steam operation would mean about 80 cents per locomotive for electric operation.

The New York Central figures published by Mr. Wilgus in Vol. 61, A.S.C.E., give $3.37 per day for steam locomotives and 55 cents for electric locomotives, or the electric cost of engine house expenses only 16.3 per cent of the steam.

Return on Investment

The estimated cost of the electrification of the 467-mile railroad considered above was $7,960,000. The return on this investment on account of the saving in operating expense was estimated at about $940,000 per year. The interest earned on the money used for the electrification of this road would thus be 11.8 per cent. If it is necessary to borrow the money for this purpose, and if it can be obtained at 5 per cent interest, there would remain a profit to the railroad of 6.8 per cent of the net cost of electrification.

Besides this increase in the railroad's revenue, it will generally be possible by operating a frequent local passenger train service with frequent stops to increase the passenger earnings and add considerably more money to the net revenue of the railroad. There are very few localities where local passenger trains are now operated which would not at least add $500.00 per year per mile of line to the gross revenue if frequent interurban cars were substituted for the local steam train. This, of course, will depend upon the density of the population, local conditions, etc. However, the increase in passenger revenue may, under the conditions in many localities, amount to several thousand dollars per year per mile of line, and is a very important consideration wherever electric operation is proposed. At the rate of only $500.00 for the 467-mile railroad considered, the increased passenger revenue would amount to $233,500.00 per year, which would add materially to the revenue resulting from electrification.

Conclusions

As stated at the beginning, the great objection to the electrification of steam railroads is the heavy expenditure involved, while the chief reason for considering the electric operation of steam railroads, aside from some special conditions at local points, was to increase the net earnings of the road. It was further stated that the answer to the question of whether th increased net earnings which would result from the electri operation would be great enough to pay interest on the cost o electrification, and besides leave a profit, could only be had b making a careful investigation of each individual road.

The example taken above was not chosen to favor electr operation but was taken to show actual conditions. It will l noted that the quantity of traffic assumed was comparative small, which of course does not favor electric operation. T

data given above, which will be found similar to those on many steam railroads, show that the traffic on many of the trunk railroads now operated by steam locomotives could be more economically handled by electric locomotives. The fact that, electrically operated, the road considered above could handle the same traffic with about 25 per cent less train mileage and locomotive mileage than when operated by steam, and with 15 per cent less ton mileage and about half as many locomotives as are needed for steam operation, is certainly deserving of serious consideration.

The overload characteristic which makes it possible for the electric locomotive to haul heavier freight trains over the short heavy grade sections than can be done by steam locomotives was illustrated above, and would indicate that considerable money now expended upon grade reductions of steam railroads would not be warranted if the road were electrically operated.

There has been considerable discussion lately as to the advisability of each railroad company building a power plant of its own, or else purchasing power from a central power company for railroad operation. One advantage of purchasing power is that the load factor of the large power companies' plants is usually high, whereas on most railroads now operating by electric power the load factor of the railroad power plants is generally low and, consequently, cost of generating power in the railroad plants is high. However, on the other hand, the load factor of a long trunk line will probably be high and the advantage of high load factor in a power company's plant will in many cases disappear.

The most important advantage in favor of railroads purchasing power for electric operation is that the heavy investment necessary for electrification would be reduced. It appears to me that the relative advantages of purchasing or generating electric power will have to be determined by local conditions. The competition between various railroads would, of course, be a very important consideration and is probably one of the principal objections to the purchasing of power from central stations. However, if a long time contract could be made with a power company at a low rate, it would have many advantages.

Another important point is suggested in connection with the electrification of steam roads and supplying electric power for them, which should be mentioned before closing this paper. At many points in the country, large steam-electric central stations

have been constructed and at the present time the amount of coal hauled from the mines to these central stations has become very large. It is also absolutely necessary that nothing delay the delivery of coal to the central stations, as the business of a whole community could be easily tied up if the electric power supply were cut off. Consequently, if in providing for future power at such points as Chicago and New York, steam-electric plants be constructed at suitable points in the vicinity of the coal mines of Indiana, Illinois and Pennsylvania, and high-tension lines be constructed from these new plants to Chicago and New York, the providing of additional railroad facilities for power plant coal hauling would not be necessary. Also, the present steam plants would insure a power supply at the distributing points during the short interruptions which occur on high-tension transmission lines.

The advantage of this arrangement to the railroads would be that if the high-tension lines were constructed upon the right of way of the railroad lines, the railroads could obtain electric power for their substations, when the roads were ultimately electrified, without the heavy expense of constructing high-tension lines of their own. The question as to whether the railroads should own the whole or a part of the power companies, is, of course, a matter which will have to be determined by local conditions.

Where water power is plentiful, as is the case in many sections of the West, the advantage of being able to tie in isolated hydroelectric plants, located at points where there is only a small market for power, to a network of high-tension lines on the railroad rights of way extending to localities where there is a market for power, is evident. Also the chief objection to the electrification of steam railroads (the heavy first cost) would be made of less importance by this arrangement.

DISCUSSION ON "2400-VOLT RAILWAY ELECTRIFICATION" (HOBART) AND "TRUNK LINE ELECTRIFICATION" (KAHLER). NEW YORK, MAY 20, 1913.

A. H. Armstrong: The two papers presented before the Institute at this meeting arrived at the same happy conclusion as to the benefits to be secured in the electrification of steam roads, but differ as to the means of securing this end. In other words, one paper advocates the single-phase and the other the direct-current motor. Instead, therefore, of following the usual procedure of side-stepping the question of single-phase versus d-c., I will confine my remarks to a broad discussion of this question as affecting the general subject of electrification.

We seem to be entering an era of electrification of steam roads, and perhaps the enthusiast for single-phase alternating trolley operating at high potential may be unduly influenced in drawing his conclusions by reason of the small tonnage carried on some of the lines where electrification is proposed. A high-voltage trolley means a minimum expense for copper and substations, but an increased cost of motive power. Looking at the matter broadly and considering that the investments made today should be based upon taking care of the traffic of to-morrow, it is reasonable to figure the first cost of electrification of any given road on the basis of an increase of 50 per cent or 100 per cent over the present tonnage now carried.

It is a well known fact that the cost of locomotives equipped with single-phase a-c. motors is higher than that of locomotives equipped with direct-current motors capable of doing similar work. When the total expense for motive power is small, that is, when the road is carrying a small tonnage and trains are infrequent, the high cost of locomotives does not become burdensome, but with increase in traffic continually demanding larger investment in motive power, the handicap of the single-phase motor is more keenly felt, and may soon overbalance the apparent initial saving in feeder copper and substation expense required with the use of the direct-current motor. On the other hand the substation and line copper expense is more or less proportional to the tonnage and speed of the moving train and is seldom influenced by the frequency of this train service. In other words, the capital invested in substation and feeder copper to take care of the movement of ten 2500-ton trains per day is generally great enough to permit the movement of twenty trains per day of equal tonnage. The feeder copper and substation installation therefore constitutes more or less of a fixed capital investment subject to a slight increase with increase in tonnage, while the locomotive investment increases with the tonnage, or even faster when track congestion commences to be a factor. We are quite liable, therefore, to turn the apparent saving of to-day into an increasing burden of expense in the future with the increase in tonnage which may be expected on our trunk lines. Should the selec-

tion of the single-phase system be based upon the apparent saving in first cost with present tonnage, the same reason may not hold if based upon the same road, carrying double the tonnage. In other words, in balancing substation and feeder copper expense against locomotive expense we are comparing what is more or less of a fixed investment against one that will increase in due proportion to future increased tonnage.

The company with which I am associated, in common with other investigators, has been for several years developing a piece of apparatus known as the mercury vapor rectifier, and the successful development of this rectifier will open up increased possibilities which we hope will accelerate the electrification movement. When developed, the rectifier affords the most efficient means known of changing from alternating to direct current. The glass tube of 10 or 15 kw. has expanded into a steel rectifier of over 1000 kw. as it stands developed to-day, and no immediate limits are in sight as to the ultimate capacity of this piece of apparatus. While the rectifier is still in the laboratory stage so far as its actual commercial use is concerned, it holds promise of being available in the immediate future and its success will have a bearing upon the electrification work of the future.

There are two methods of using the rectifier.

First, it can be placed upon a locomotive equipped with direct-current motors and transformer used in connection with 11,000-volt single-phase trolley distribution system. In this case the rectifier will operate single-phase, will produce a current that is unidirectional, but the pulsating character of the current may demand special construction of the d-c. motors. The single-phase step-down transformer will also be special in character in order to provide for the needs of the rectifier.

In general the advantage offered by the use of the rectifier on the locomotive lies in the possibility of using direct-current motors instead of single-phase, and thus obtaining the admittedly better constants of that type of motive power. I know no authority who will question the superiority of the direct-current motor over the single-phase a-c. motor as applied to traction work, and the rectifier placed upon the locomotive itself combines the good qualities of the d-c. motor on the locomotive with all those advantages claimed for the single-phase high-tension trolley distribution.

Second, the rectifier may be placed in substations located at the most desirable points along the right of way. In this case the rectifier will use balanced three-phase energy of any frequency, taking energy equally from all three legs of the circuit, and by using a multi-phase rectifier it will result in giving direct current in which the fluctuations are largely eliminated. This will enable such a rectifier substation to feed standard direct-current motors and will moreover provide a balanced three-phase load which can be supplied from existing transmission

systems at any frequency without causing undesirable interference with lighting and miscellaneous load distribution. The general advantage of locating the rectifier in the substation is that its efficiency will probably be from 10 to 15 per cent higher than that of a motor-generator set, and furthermore the rectifier is adapted to deliver direct-current energy of any potential required and is therefore admirably fitted to supply 2400 volts or higher to the trolley. Furthermore, the substation, being without moving machinery, can be operated with a minimum of attendance and may show an attractive reduction in first cost over motor-generator set substations.

Introducing the rectifier substation upsets our preconceived ideas as to the proper relation of cost of substation and feeder copper, as the rectifier substation shows a very marked increase in efficiency, decreased cost of complete substation, and we may even anticipate the time when it can be operated without attendants in such localities as would require no attendance with a a step-down transformer station. The success of the rectifier therefore means just as much to the high-voltage direct-current motor system as to the single-phase trolley.

In conclusion, it seems to me that, looking at the matter broadly and without enthusiasm but with full knowledge of the operating facts of to-day and the possibility of the immediate future, the single-phase commutating motor as such is destined to become more or less a thing of the past. It is even a grave question whether the single-phase trolley locomotive of any description, with its interference with neighboring telephone and telegraph lines, the difficulty and expense of providing single-phase current without erecting a generating and distributing system devoted solely to railway apparatus, and with the high first cost and cost of maintaining the motive power, do not all together present difficulties which make the single-phase trolley system undesirable, viewed from the standpoint of the high-voltage direct-current motor and its possibilities.

While the Butte, Anaconda & Pacific direct-current locomotive was designed and is now in commercial operation at 2400 volts, the company constructing it also built and tested high-potential direct-current apparatus up to 5000 volts with entire success, and no objection can be raised as to the practicability of using this high potential if local conditions demand it.

As a final remark I wish to state that as evidence of the possibility of having the mercury rectifier available in the near future, there was run at Schenectady during the past week a test with one of the Butte, Anaconda & Pacific 80-ton locomotives and a 1000-kw. mercury vapor rectifier, during which test no restrictions whatever were placed upon the motor output, such as operating at full load, slipping the wheels, etc. It is probable that within a few months there will be equipped for demonstration both a locomotive and a stationary substation containing mercury rectifiers which will be put into commercial

operation to secure the active experience needed to make this type of apparatus commercially available.

F. E. Wynne: In going over Mr. Kahler's paper I noted his tables on the division of time for steam and electric locomotives, Tables IX and X, and thought it would be useful to plot these (Figs. 1 and 2) so as to show at a glance what might be not apparent in these tables without study. The values for steam are actual results, and those for electric locomotives are Mr. Kahler's estimates.

The top section in each figure represents the time on the road; the bottom section represents the time spent in the engine house. It is interesting to note that for the passenger locomotives these sections are approximately reversed for electric and steam operation. On the freight engine the difference is not so great, although the electric engine makes considerable gain over the steam. In the freight diagram there is a certain area representing the time spent in sidings; in other words, the locomotives are ready for operation but are not in actual motion on the road.

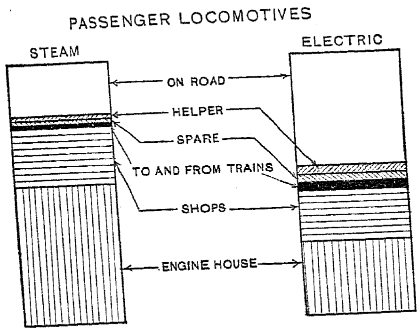


FIG. 1

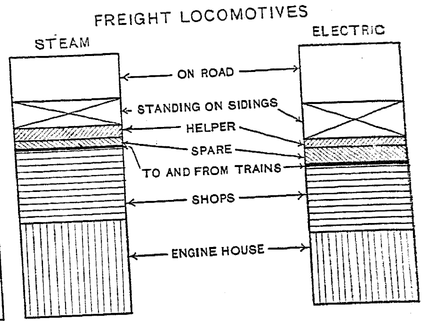


FIG. 2

Mr. Kahler has used an electric locomotive of much greater hauling capacity than his steam engine. The steam engine weighs a total of 185.1 tons with loaded tender, and has a maximum tractive effort of 43,000 lb. The electric locomotive weighs 110 tons, all weight on drivers, and has a maximum tractive effort of 55,000 lb. Applying these tractive efforts to show what can be done on short ruling grades, I have worked out Fig. 3, for grades from level to a maximum of 4 per cent, showing the ratio between the maximum tonnages which the electric and steam locomotives can haul. On level track the electric engine hauls 38 per cent more than the steam engine, and on a one per cent grade approximately 50 per cent more. Grades up to 4 per cent are shown because such grades occur on branches of existing steam roads. Fig. 3 is based on train friction of 6 lb. per ton for trailing load, 15 lb. per ton for the electric locomotive and 25 lb. per ton for the steam engine.

Mr. Kahler's paper refers to gasoline motor cars and gasoline-electric motor cars. In this connection I think it is well for us to remember that most of the comparisons which have been made between steam locomotive operation costs and the costs of these self-contained motor cars have considered everything in figuring out the cost with steam, while in giving the cost of the self-propelled units nothing is included for track maintenance, signaling, despatching, or general expenses. So the comparison is not always a fair one.

I was very much interested in the table in which Mr. Kahler shows the limiting grades for both electric and steam operation, and where he shows the tonnage which can be handled in the various districts with each type of engine.

I think the chief value to be found in Mr. Kahler's paper, aside from the actual records of steam operation which he has submitted, is the fact that he has shown the way to attack the problem of ascertaining whether it will pay to electrify a steam road; he has shown how to analyze steam operation and estimate the probable saving by electric operation. His results are very interesting, showing, for electric operation, an annual saving of $940,000.00, on a net investment of approximately $8,000,000.00 or a gross investment of approximately $10,000,000.00. In other words, if we take account of the salvage for steam locomotives, the return on the investment is approximately 11½ per cent, or, if the steam locomotives are worn out and there is no salvage at all, we still have 9½ per cent.

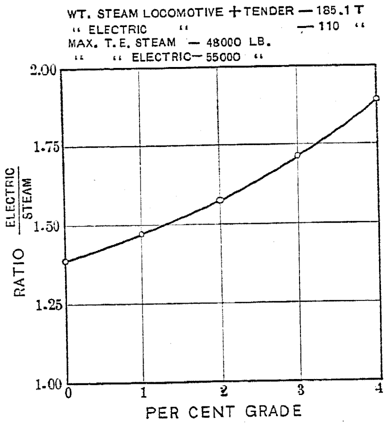


Fig. 3—Relative Hauling Capacities of Electric and Steam Locomotives on Short Ruling Grades

Table XXI, page 1216, throws some light on the estimate of locomotive maintenance made by Mr. Hobart. The figures given in Table XXI show that maintenance is largely affected by the class of traffic in which the locomotive is used. In high speed traffic, where the mileage is great, the cost per engine mile is lower than with low speed service. With the exception of those for the helper engine all of the figures given by Mr. Kahler are below 10c. per mile per 100 tons of engine; the passenger engines show between 4c. and 5c. and the freight engines between 6c. and 7c.

In Table XXII, a most interesting item is that boiler washout requires 42 per cent of the steam locomotive's engine house expenses.

In connection with Mr. Hobart's paper, I have noticed some things which steam railroad men may see, and, knowing they are somewhat unusual for steam operation, may be led to doubt the value of other figures in the paper.

On page 1153, for a certain class of engine and train, the pounds of coal per drawbar horse power-hour are determined. When converted into other units it shows, on a basis of 14,000-B.t.u. coal, the gross ton-miles hauled are 7.6 for each pound of coal; and, on a basis of 11,000-B.t.u. coal, 6 gross ton-miles for each pound of coal burned. These values, I believe, are rather high, even in passenger service, as I have some records of steam operation which show that this figure for both freight and passenger services is between three and a quarter and four gross ton-miles for each pound of coal burned.

The use of bogey trucks is mentioned for locomotives exceeding 45 miles per hour maximum speed. In this connection it would be of interest to know what is considered the limit of dead weight per axle on these leading trucks.

On page 1155, the writer gives some rather high over-all substation efficiencies; 89 per cent for dense service and 78 per cent for sparse service. These values are high, and if worked out for the usual load factors, with motor-generator sets and including the transformers and exciters, these percentages would be decreased from 7 per cent to 10 per cent. Otherwise, it is rather hard to account for some of the large differences between the input and the output of substations on actual roads.

Mr. Hobart informs us that "for a given life of the contact roller, tests reveal the following relation between the speed of a pantagraph trolley and the current which can be collected," that with speeds varying from 10 to 60 miles per hour the roller contact collects from 1200 to 300 amperes, respectively. These figures seem very high, and it would be very interesting to the Institute to know what life of the contact roller can be secured with a roller collecting these currents at these speeds, as the roller is somewhat expensive to renew.

The paper contains an apparent inconsistency in that 34,000 lb. is taken as the drawbar pull for two of these Butte, Anaconda & Pacific locomotives, and the corresponding speed is taken at 14 miles per hour. On the next page the continuous tractive effort is given as 25,000 lb. each, or a total of 50,000 lb., at 15 miles per hour. Evidently this speed of only 14 miles per hour at 34,000 lb. drawbar pull takes account of the large line drop that goes with a direct-current installation. On the other hand, when it comes to estimating the current to be collected, 2400 volts at the locomotive is the assumed voltage.

If the speed curve of this particular locomotive were available, I think we should find a somewhat larger current to be collected at a somewhat higher speed.

The gross-ton-miles per ton of coal burned are given as 3.1, which is in line with the information we have.

Reference is made to 44 miles per day, average for 365 days, as being a high figure for Mallet locomotives. Some records of Mallets in mountain service averaged over periods of one year or more show a minimum of 48 miles, and a maximum of 75 miles, per day, and I do not think 44 miles is an exceedingly high figure, particularly as the higher figure includes for each locomotive at least one month out of service for general overhauling.

In connection with the 96-mile electrification of a mountain grade, I think too many electric locomotives are assumed; that is, 48 double-unit engines, when the maximum number of trains on the line is 28, as shown in the foot-note, page 1176.

The paper states that on a basis of 8 lb. per ton train friction, and a grade of 2.2 per cent, the drawbar pull is found to be 94,000. This is, then, arbitrarily increased 36 per cent to allow for bad weather conditions. Of course, the effect of grade is the same in all kinds of weather, therefore, the result of making this increase of 36 per cent in drawbar pull is that the friction is run up to 26.7 lb. per ton, which is very high, even for bad weather. If we use these figures, we find that the engine, with 128,000 lb. drawbar pull, for 1800 tons trailing in bad weather, will handle 2560 tons trailing load in good weather. Thus, the tonnage rating for bad weather is only 70 per cent of the good weather rating. This difference is much greater than that in common use on steam railroads.

Another indication that the total number of electric locomotives is very high is that the average works out only 75 locomotive-miles per day, per electric engine.

The paper gives some indications of the permanent investment to which Mr. Armstrong referred. Taking the cost of overhead and substations, and assuming the substations are on a basis of 200 per cent overload for short periods, it works out to $37.00 per kw. for substations and an overhead feeder system of 2,000,000 circular mils of copper in addition to the trolley. These figures seem high for permanent investment; for that reason I do not think 2400 volts d-c. is most suitable for heavy traffic. As it stands, 2400 volts is not sufficiently high; it may be fit for certain traffic, but for heavy traffic it is certainly too low.

Referring again to the matter of train resistance, we read that in descending "the power required for propulsion will be negligible for most of the descent, nevertheless, steam must be maintained in the boilers, and also, owing to the high frictional resistance of the Mallet engines, power will be required for all grades materially lower than the average value of 1.5 per cent." If we work this out for a 250-ton Mallet engine, with trailing load of 600 tons pushing it down hill, we obtain a result which looks rather high; that is, 80 lb. per ton frictional resistance for the Mallet.

The comparison is made on the basis of different amounts of

traffic for steam and electric operation. I think it should have been worked out to handle the same traffic, in which case the electric locomotive would have made a better showing.

Referring to page 1187, I ask if "the correct basis for estimating the commercial results to accrue from the electrical operation is to compare all those items which are affected by the use of electricity instead of steam," why is it that this is "inconsistent with the retention of the forms which have become customary in analyzing the results of steam operation"? It seems to me that is really the good way to get at the answer, rather than the inconsistent way.

In connection with Mr. Armstrong's remarks as to increase in traffic not materially affecting substation or feeder cost, I would like to call attention to some installations made in the past, where the substation and feeder costs have been materially increased when the traffic was increased. The Pittsburgh, Harmony, Butler & New Castle Railway, at 1200 volts d-c., was one case. Another was the 600-volt d-c. electrification of the West Jersey & Seashore Railroad.

George Hill: I have been impressed while sitting here listening to these two papers and the discussion of them, and from my own acquaintance with the trend of railway electrification, with the fact that railway men throughout the country are taking a greater and greater interest all the time in the electrification of steam roads.

In these days of ever-increasing effort toward high efficiency, and the desire to get the best and most out of everything that is done, it is gratifying to the electrical engineer to see the steam railroads turning more and more to the use of electrical power. It is especially gratifying to see that this is being done largely in a consistent and logical manner. That is, the roads which are adopting electrification, especially in connection with the handling of freight, are doing it by applying the electrification remedy to those points where it is most needed; I refer particularly to heavy grade work. I may mention at this time an example of this in the electrification of the Norfolk & Western Railway, the mountain grade division called the Elk Horn grade, between Bluefields and Vivian, in West Virginia. It is generally known that this electrification is in progress, and it is one of the cases where it has been found that a very material saving and a very satisfactory return on the investment will be effected by electrification. Our firm has had occasion to investigate and report on a number of electrification propositions of this general character, and it is evident that for many cases of this heavy mountain-grade character, electrification will make a very satisfactory showing, not only in the savings under equal conditions, but also by greatly increasing the capacity by increasing the speed and improving the reliability of the service, and thus the earning power of the property.

W. S. Murray: I realize that it is necessary for me to cut my remarks short, and this has been made possible by most of the wind having been taken out of my sails by the very excellent line of inquiries which have been asked by Mr. Wynne with regard to Mr. Hobart's paper.

I was very curious indeed about some of the statements in that paper, and doubtless the answers to Mr. Wynne's questions will bring the information I most desire.

There is one thing I want to try to emphasize that has struck me forcibly in the matter of electrification, and that is this: Electricity is nothing more than an agent to do the same work that steam has been doing for about 80 years, and in settling these problems of electrification, both with reference to level and grade conditions, it seems to me the first thing we electrical engineers owe to our railroads in this country before we begin to electrify them is to see if they have been reduced to the best steam basis.

1. We have been prone to base our opinions and our conclusions on electrical figures that have not got for themselves the same basis that steam has. Therefore, to repeat, we must get the territory to be considered upon a proper steam basis before we take up the matter of its electrification. Now, as the railroads have grown in age, so have the efficiencies gone down. Certain local conditions and matters that appertained to the relation of traffic and equipment schedule have not been caught up as they should have been; and so when we electrical engineers go into them, we set up first our wonderful schedules, and show the electrical economies above steam, and capitalize the project on a basis that takes care of the construction bonds, indicating a magnificent dividend on the electrical investment. Now, that has been the tendency and I think that we should be extremely careful to avoid such practises.

Now I want to draw attention to the fact that a steam locomotive can, if the fireman's arm holds out, develop its maximum tractive effort continuously. That is a very important point.

2. An electrical engine has no fireman's arm between it and its tractive effort, but it has in its place a temperature rise which must be reckoned with.

3. The electrical engine has the advantage of the steam engine for sustained horse power; but the steam engine has the advantage of the electrical for sustained tractive effort, *ex* fireman's arm.

It is within the realm of possibility that steam locomotives are to be of a different order in the future from what they have been in the past. Oil burning and automatic stoker locomotives will make us electrical engineers hustle to prove our case.

The electrical engineer who has a clear-cut understanding of the foregoing facts, knows their value, and so I can only draw your attention to Mr. Wynne's figures. He shows an interesting

line of ratios in regard to steam and electrical engines on different orders of grades. The most important part of Mr. Wynne's diagram is not shown, and that is the length of grade involved. These papers which we have been much interested in tonight are of an academic order; the real physical conditions of the problem are not sufficiently discussed.

There are many figures which Mr. Kahler has brought out which are most interesting and absolutely true; and yet the real question is their proper correlation and application to the specific problem in mind.

I want to extend a warm hand of friendship to my friend, Mr. Armstrong, who has joined me on the single-phase bandwagon.

The power houses of the single-phase and direct-current systems are about a stand-off. The direct-current locomotives cost less than single-phase locomotives, but the distribution system for the single-phase system is by far the more economical of the two. Now you see this interesting combination where we secure a minimum cost of power station, minimum cost of distribution and finally the minimum cost of locomotive. Mr. Armstrong has indeed built a beautiful bridge, over which I am very glad to walk and meet him half-way. As I have always had to admit that the cost of single-phase locomotives was more than that of direct-current locomotives, since from the time they have been manufactured they have necessarily been heavier, I have been as forcefully required to admit that the distribution system for the single-phase system possessed such inherent characteristics of economy as to far offset the greater cost of the a-c. locomotive, and if single-phase current for heavy trunk line traffic has now been accepted as the economic form for electric train propulsion my position would be truly illogical not to welcome with Mr. Armstrong the coming of the rectifier locomotive, which will bring out still more its economic characteristics. In the absence of the rectifier the single-phase motor was a necessity to make use of the economical single-phase distribution. In the last analysis of the true economics of any heavy trunk line electrification project it will be found that the single-phase motor rules out its direct-current brother. The direct-current motor has put up a good but a losing fight for its position in this field, and through the medium of the rectifier let us hope that it regains its former position. I am interested in the type of motor only so far as the position it may take in the consideration of the electrification as a whole. The fact that the direct-current motor may replace the single-phase motor through the medium of the rectifier, but stamps the electrification all the more as being single-phase, for the reason that the distribution system has made that end possible.

A. H. Babcock (by letter): The two papers by Hobart and Kahler dealing with trunk line electrification merely serve to emphasize a conviction that has been growing steadily in my mind for some years, that generalization with reference to

trunk line electrification is extremely dangerous. In hypothetical cases, or even in cases where only a preliminary estimate is required, often curious results are reached by the use of improper bases on which to form the arguments leading to conclusions. The incorrect premises may be due to a partial study of the case involved, or a desire to make a very favorable showing in order that capital may be interested to investigate farther, or to a variety of causes, but the result is the same; while in the hypothetical case, from a given set of assumptions one may argue himself into almost any desired position, in practise the hard and unyielding physical facts are met.

During the last ten years my office has made reports on every mountain railway exit from the Central California valleys, and on other mountain districts in other parts of the West Coast country. Often these reports have been the result of agitation on the part of power companies with a surplus of power for sale. In other cases they have been the results of pressure exerted by the manufacturers on the executives of the railway companies. In not a single one of the reports that have been made in considerable number, as stated, could it be said "that the operating economies which have been effected by superseding, with electric locomotives, the steam locomotives on such railways, are enormous and are indeed of such amounts as to defray in a very few years the initial outlays for substations, for feeders and contact-conductors, and for electric locomotives" (Hobart). Quite the converse is the fact and in every case on which a report has been made the conclusions have been adverse to electrification on precisely the reverse of the facts in the quotation above cited.

Whenever the request for such reports has been started by a power company, statements relative to "the very low cost at which the large hydroelectric supply companies in the West can profitably sell electricity" (Hobart), have been made by officials of the power companies; but it is a significant fact that when the same power companies have been confronted with the physical facts of the railway company's requirements as to quantity of energy, maximum demands for power, and load factor, invariably the rates quoted have been quite prohibitive, notwithstanding the fact that usually they are lower than those assumed by the authors of these papers, (Hobart, page 1180 and Kahler, page 1222). As a matter of fact, with fuel oil on the West Coast at ordinary market rates, say 70 to 80 cents a barrel, an energy rate greater than 5 mills is utterly prohibitive, as far as water power purchase is concerned; moreover, the annual load factor, although it "should not get lower than 60 per cent," (Kahler, page 1222), seldom rises above 20 per cent as a matter of fact, and as a rule the total energy charge can be wiped out of the annual statement without making a material difference in the conclusions, so small a part does it play in the annual operating cost when the fixed charges and other elements of operating expense are taken properly into account.

Not one of the projects that have come under my notice conforms in the slightest to the following—" But when it is understood that these Western hydroelectric companies already have enormous loads connected to their systems, it will be seen that the fluctuations of a couple of thousand kilowatts, more or less, imposed by the intermittent operation of a few freight trains, is not a factor of consequence" (Hobart, page 1162). Our freight trains require from 4000 to 4500 kilowatts apiece and thus far no power company on the West Coast, however large its service may be, has yet been found to view with equanimity the possibilities of a number of such loads being thrown instantly on or off its systems; furthermore, the above power demands are of such duration that the figures given represent the continuous capacity of locomotives per train.

The fact that so many men engaged in the study of these problems discuss them from the standpoints of the authors of the two papers from which quotations have been taken, indicates, of course, that in other parts of the country the extremely severe conditions of the West Coast mountain railroading do not obtain. It is obvious also that were I, whose experience in such estimating has been confined exclusively to West Coast work, to attempt to generalize from that experience and the information gained in the study of these projects, the result, if expressed publicly, might be, to say the least, embarrassing to me and amusing to some of the eminent gentlemen who have favored the Institute with general discussions in the past. Precisely this difficulty has been met with in discussing West Coast problems personally with Eastern factory engineers, and it was not until these same engineers came West and investigated on the ground for themselves that a mutual understanding of each others' words was reached. With this thought in mind the foregoing remarks are submitted, not at all in criticism of the papers referred to, but as supplementary thereto.

H. Y. Hall and G. W. Welsh (by letter): Mr. Kahler's paper states that only ten electric locomotives would be needed for the through passenger trains; this on a 468-mile line with three engine districts and three through passenger trains each way per day. Assuming that it is the intention to operate the 468-mile line electrically with three engine districts, as indicated by the paper, an examination of the train sheet shown in Fig. 2, for the through passenger trains, shows that there are actually required for the operation of three through trains each way per day, three locomotives on engine district No. 1, four on district No. 2, and three on district No. 3, or a total of ten locomotives actually required, assuming all trains to be on time and no extra trains. This does not include any locomotives " in shops, spares, in engine house, running to and from trains, and in helper service." The time saved in taking water mentioned is small for passenger service and for the above train sheet will not reduce the number of electric locomotives required for actual

service. On most western railroads during the heavy tourist season, it is practically an every-day occurrence to run passenger trains in sections; and on days of extremely heavy tourist travel, the number of trains is often increased by 40 to 50 per cent. Judging by the figures given in Table VI, it is evident that Mr. Kahler does not consider that more than one section of any train will ever be necessary. In this respect the road considered by the author is unique, since it is the only road in the western part of the United States which can run without extra trains. It would seem that an allowance of twenty passenger locomotives, instead of ten, would not be excessive on both the grounds of reliability and actual traffic.

Referring again to Table VI, under "Freight Trains," the ratio of maximum day to average day appears to be exceedingly low. On some of the through lines in California, it is not unusual during the heavy fruit shipping season to have a maximum day of 2 to 2½ times the average day throughout the year. Evidently, the number of locomotives must be sufficient to take care of the maximum day. In steam operation, on a large system, the usual way of taking care of this excess traffic is to rush all available locomotives from other parts of the system to help out the congested district. This is not possible with electric operation unless the entire system is operated electrically. Another point is that freight trains very seldom run on time and although they may be dispatched at stated intervals from one terminal, they rarely reach the other terminal with the same time interval between them. Therefore with the forty-three freight locomotives (that is, electric freight locomotives,) shown in Table X, we think the road under consideration by Mr. Kahler would find itself frequently with its cars at one end of the line and its locomotives at the other. Of course, in times of emergency, electric locomotives can be run over more than one engine district without injury, but in our opinion the actual requirements of the road under consideration would be more nearly realized if the number of freight locomotives given in the paper were increased by 50 per cent, or say to 60 locomotives.

It should be noted that under "Locomotive Repairs," the cost per locomotive mile given for single-phase locomotives is based on the published reports of two roads operating direct-current apparatus. It would be interesting to know what is the repair cost per mile on single-phase locomotives, but only one road in the United States operates a sufficient number of these equipments to give reliable information, and to the best of our knowledge this has never been published.

The "Estimated Cost of Electrification" given is altogether too low to be conservative.

It is not possible, for $5000 per mile, to build a double-circuit steel tower transmission line of sufficient factor of safety and with sufficient copper to hold the losses and regulation within the proper limits, especially with low power factor lagging current

as would obtain with a single-phase electrification. This cost should be increased to $6000 per mile.

Judging from the extremely low cost given, the author is not considering the use of catenary construction. For the class of service required, the catenary construction would be none too good. At a Pacific Coast point, located close to the source of supply of good and cheap cedar poles, it costs $2175 per mile (not including engineering and contingency) for single-track bracket, 1500-volt, d-c. catenary construction. In this case $2500 per mile should be used, on account of higher voltage, generally stronger type of construction for main line operation and to cover installation of feeder.

The double-track span construction would cost $4000 instead of $2600 per mile.

The four- or more track bridge construction would cost nearer $15,000 than $9000 per mile.

With the increase in first costs and increase in number of locomotives as given above, the total first costs would be $12,698,209 instead of $9,972,000, while the net estimate would be $10,686,209, instead of $7,960,000.

The total of maintenance of overhead structures and substations, Table XV, is too low to cover necessary emergency gangs, repair gangs, patrolmen, material, etc., for the proper maintenance of a 468-mile section of a single-track main line with so dense a traffic. This item should be increased at least 60 per cent.

Referring to Table XVI, Mr. Kahler has based his depreciations upon estimated first costs, excluding engineering and contingency. If in making estimates for immediate work it is necessary or desirable to add a contingency to cover fluctuations of material costs and unforseen items or difficulties, it is certainly necessary to add a contingency for work to be done 20 or 30 years after the making of an estimate. It is common knowledge that to do certain classes of work, it now costs three times as much as it did 20 years ago. Then again, it would not be desirable to do the work in the same manner twenty years hence, so it will be necessary again to pay for engineering. Including the engineering and contingency would increase the depreciation 15.5 per cent. A life of 15 years on poles and fixtures (item 18), would be nearer the accepted value than 20 years, as given, so the depreciation should be $6\frac{2}{3}$ per cent instead of 5 per cent. With the increased first costs, the inclusion of engineering and contingency and increase in depreciation rate on "poles and fixtures," the total depreciation of overhead structures and substations would be $226,046 instead of $144,084.

The total of depreciation of electric equipment, Table XVIII, with increased number of locomotives, as noted above, and with engineering and contingency included in the cost upon depreciation, would be $107,115, instead of $64,740.

With the increases given above, the total cost of electric

operation (Table XX) would be $3,090,178 instead of $2,908,409 and the annual saving would become $758,231 instead of $940,000. This would give a net return of 6.8 per cent, which with interest of 5 per cent, would give a net profit of 1.8 per cent on the investment, which is too small a profit upon which to base a recommendation for electrification, as this estimated profit would be entirely wiped out if the "actual" expenses of electric operation were 7 per cent higher than the estimated operating expenses.

Mr. Hobart gives a first cost of $8,500 per mile for overhead contact line, rail bonding and feeder copper. Several paragraphs above he gives the annual efficiency, locomotives to substation, as 93 per cent. This would give an efficiency of 91.1 per cent during the heavy traffic period. With a substation spacing of 26 miles and 90-lb. rail, single track, the cost of the positive feeder alone (excluding trolley), to give efficiency of 90 per cent on maximum day, would be $6600. This is based on the use of aluminum at 33 cents per lb. erected, which is equivalent to copper at 15½ cents per lb. erected. This calculation is based upon a minimum condition of only one train at a time between substations, whereas with the speed of trains and interval of starting given, it is possible to have two trains at a time on the up-grade between substations. In our opinion, to obtain an annual efficiency of 93 per cent, it would be necessary to spend at least $12,000 per mile for overhead contact line (catenary construction), rail bonding and aluminum feeder. It should be borne in mind that on mountain divisions, it is necessary to blast at least 60 per cent of the holes for setting trolley poles.

During the maximum traffic period of 18 1800-ton trains each way per day as given, with 12,200 kw-hr. per locomotive journey and the same percentages added as shown on page 1180, the average load per substation will be 6150 kw. instead of 3200 kw. as given. With a load factor of 25 per cent, the maximum load would be 24,600 kw., but with an average of 6150 kw. the load factor would probably be as good as 35 per cent, which gives a maximum of 17,600 kw. per substation.

With an average load of 6150 kw. the heating load per substation would be not less than 8200 kw., which would require 8000 kw. for regular service and 2000 kw. for spare, making a total installed capacity of 10,000 kw. per substation, which at $30 per kw. would amount to $300,000 per substation instead of $160,000, as given, or as a total for the four substations, $1,200,000 instead of $640,000 as given.

With the above changes, the cost of overhead construction, bonding and substations would be:

96 miles overhead and bonds at $12,000..	$1,152,000.
Sidings, same as given by Mr. Hobart....	84,000.
Substations..........................	1,200,000.
Total...............................	$2,436,000.

On the basis of 16 per cent of first cost as given by Mr. Hobart, the fixed charges, maintenance and operation of substation (not including electric energy), would amount to $389,760 instead of $246,000 as given.

Note 17 states that, " It is desired to err on the side of favoring the steam locomotive whenever there is room for divergence of opinion." In view of this statement, it is not quite clear why he has used the 250-ton Mallet locomotive in handling the 600-ton train, or three of these locomotives for an 1800-ton train, when there is in actual service today a 300-ton Mallet locomotive which will haul a 900-ton trailing train on an average grade of 1½ per cent at average speeds in excess of the 12 miles per hour assumed in this paper. Naturally, if fewer locomotives of a larger rating are used, the operating costs, such as fuel consumption, locomotive repairs, enginemen's wages, etc., will be materially reduced.

Also, the cost of 250-ton Mallets is given as $45,000. The 300-ton Mallet mentioned above costs new approximately $33,500, and the heaviest Mallet locomotives ever built (weighing 425 tons) cost slightly less than $44,000. It is evident that the figure of $45,000 is much too high.

The foregoing analysis of Mr. Hobart's paper, (also of Mr. Kahler's paper), is based on West Coast operating conditions, as developed in the study of some of the most important heavy trunk lines operating over the Sierras. It shows that while he has made a favorable showing for the very general case he has assumed, his results, if applied to any of the concrete cases known to the office with which we are connected, would be disappointing to those who might be induced thereby to invest money, and who expect profit. Based on our experience, his estimated costs for overhead construction and substation equipment are very much too low; hence his electric operating costs are correspondingly low; he has considered steam locomotives only two-thirds as powerful as those now in service on our lines, and in his estimate of first cost, he has taken these comparatively small steam locomotives at a unit cost essentially the same as was paid for the largest steam locomotive ever built for West Coast work. His estimated first costs for steam locomotives are at least 30 per cent higher than West Coast practise shows to be reasonable, and his estimated steam operating costs are correspondingly high. In general, then, according to our experience, the costs of steam operation have been magnified and the costs of electric operation minimized, in this, as in many other such very general solutions of a very complex problem.

F. W. Carter (by letter): The subject matter of the present papers is of great importance and discussion cannot fail to furnish valuable information. I think such papers as these are best written with a view of instructing or convincing the railway engineer rather than the electrical engineer, and the greatest care should accordingly be taken to avoid an undue bias in favor

of electrical working. But from the nature of the case, in which comparison is made between an established system and a newer rival, the figures for the established system are likely to be based on actual operation, and to cover a number of more or less trivial or accidental circumstances which are apt to be overlooked in making the comparison; I think there are signs of this tendency in both the present papers. For instance, in Mr. Hobart's express passenger proposition he adopts the figure of nine lb. per ton average train resistance; this is a reasonable figure, considering that the mean train resistance is necessarily greater than the train resistance at the mean speed, and moreover that the figure includes the effects of curves, adverse weather, and other difficulties of the route. He, however, deduces his coal consumption directly from the work done against train resistance, suggesting an equipment efficiency of the order of 87 per cent. But the energy dissipated in final braking is of the order of 75 h.p-hr., and although townships are more sparsely scattered in the United States than in England, it is doubtful whether a typical 100-mile run should have been assumed without some speed restrictions, each consuming, say, 60 or 70 h.p-hr., while a signal stop is not likely to be an infrequent occurrence. Altogether, I think that to accord with actual operation, the coal consumption in the electrical case would have been better assumed 15 or 20 per cent greater than Mr. Hobart finds it to be. In the steam case I surmise that the corresponding figure is derived ultimately from the integral consumption in actual service, and therefore includes the effects of all the normal circumstances of such runs.

Mr. Kahler, again, seems to me, however, to have made his calculations without due regard to limitations that the traffic department may impose. He shows that it is possible to handle a certain tonnage of freight with but few more than half the number of locomotives in service than would be required under steam operation. This is certainly an engineering possibility, but if it is a commercial possibility, it is a pretty sure sign that the line is congested, and the proposition takes on an entirely new aspect on this account. Mr. Kahler assumes the average weight of train as 80 per cent of the maximum. Under English conditions, I believe this figure is nearer 60 per cent, but however this may be, the effect of increasing the capacity of the locomotive would in general be to reduce the figure by, say, 10 or 15 per cent. Many light trains would go forward at the instance of the traffic department without reference to the ultimate capacity of the locomotive. The number of freight locomotives required in actual service at any time would, I think, be nearly as great with electric operation as with steam.

Comparing Tables IX and XIII, I am inclined to think also that the number of electric passenger locomotives required is somewhat underestimated, for the exigencies of traffic would

keep locomotives waiting in service, much as it does under steam operation. It would seem that in the case of the Butte, Anaconda and Pacific electrification, 23 steam locomotives are replaced by 17 electric, no such reduction as Mr. Kahler finds possible.

I note that Mr. Kahler has assumed the single-phase system of operation, but he seems to have based his estimate of locomotive repair cost on results obtained with continuous-current locomotives. Since the repair of the single-phase electrical equipment has been found to cost something like three times as much as for the corresponding continuous-current equipment, I am disposed to think his figures here a little too low, and I also think the number of his laid-up locomotives is on the low side for the same reason. His energy consumptions, too, appear to me somewhat low for normal operation, which Fig. 3 shows to have been contemplated, the frequent stops and intervals of running with brakes applied resulting in the dissipation of much energy. Although my contribution to the discussion is generally of the nature of criticism, I should like to express my appreciation of these very able and suggestive papers.

F. C. Merriell (by letter): The financial showing which has been so conservatively developed in these discussions finds very little consideration from railway operating officials, because of two fancied weaknesses which are believed to attend electric traction.

Frequent failure of electric locomotives in heavy traction service is believed by steam railway men to be inherent in a device, which to them, appears to be more complicated and less substantial than the steam locomotive, and even the most elaborate and painstaking analysis of the economies of electrification will not avail against this belief, unless the operating experience of present electrifications shall prove that analysis to have been very conservative. The fact that partial failure, of a steam locomotive is but little better than total failure while partial failure in an electric locomotive will usually not prevent it from getting in the clear, and perhaps making some progress until help can reach it, will have to be strongly urged even after the railway man has been convinced that of the two devices the electric is the simpler and the more substantial.

As appears in these discussions, the first divisions to be electrified will be those where heavy mountain work occurs and pusher service is required, and as these places are nearly always at high altitudes and subject to severe weather, steam railway men now believe that electric traction will, in such locations, meet obstacles which it cannot withstand. They admit the inefficiency of the steam locomotive to cope with extreme cold weather by their customary reductions in train tonnage as temperatures fall, which follows quite as much from the fact that the engines cannot make steam as from the poor conditions for traction. The electric traction man, on the other hand, expects his

motors to operate at greater loads during cold weather and is thus enabled to push his train tonnage up to the limit imposed by the condition of the track. Experience of heavy traction lines and such electrifications as are now in operation shows that distribution systems can be maintained without undue expense against the coldest and worst weather and will thus, contrary to the prevailing notion, cause less interference with traffic than engines which will not steam. The analysis of traffic movement on western roads will usually show that a part at least of the greatest congestions tends to lap over into extreme cold weather, as for instance the business of roads handling both deciduous and citrus fruits, which business will require much tonnage in deciduous fruit to be moved at the beginning of winter, while tonnage in citrus fruits will become quite large before it ends, all of which should tend to make the advantage of electric traction appeal more strongly, as soon as the electrical fraternity is able to assure the railway operator that he can rely upon electrical machines for continuous service and few failures.

The stimulation to local main line traffic which is mentioned as possible with electrification can also profitably be extended to feeder lines, and many of these which now operate at a loss might be brought nearer to a paying basis than they now are. It is the contention of railway officials that feeders as separate entities rarely make a profit (being principally valuable for the traffic they bring to the parent system), but the same standards of service, convenience, and efficiency, which the flexibility and economy of electric traction effect upon main line traffic, will without doubt render feeder lines more justifiable than they are considered at present.

H. F. Parshall (by letter): With reference to the two papers by Mr. Hobart and Mr. Kahler, I may say, speaking generally, that both papers would have been more convincing to railway engineers if accompanied by figures showing representative results obtained in good steam practise. According to my own experience and observations, both have assumed better results than are being obtained or are likely to be obtained in steam locomotive practise. The paper by Mr. Insull gave results obtained on several roads which led to the conclusion that the cost by steam locomotion is much higher than is commonly assumed. Personally, I think the time has passed when the electrical engineer need adopt the position of apologist to the steam engineer.

The electric locomotive is *ab initio* the cheaper machine to operate. The real problem is to determine at what point the density of traffic is sufficient to justify the electrical installation. The fixed element is the conducting system between the locomotive and the power system. The cost of fuel of the electrical system under ordinary conditions is not more than half that with the steam system, but, on the other hand, the cost of the steam locomotive installation is not often more than 20 to 25 per cent

of the cost of the electric locomotive installation including the conducting system.

Under favorable conditions the cost of maintenance of the two systems is not very different. Under some conditions, however, the cost of maintaining the steam locomotive system must be materially greater. With cheap hydroelectric power and expensive coal, the electric system pays for itself with moderate traffic density. With increasing labor difficulties and increasing cost of fuel, the case of the electrical system becomes every day stronger, as less men, less skilled mechanics and less fuel are required with the electrical system.

From a strictly operative point of view, my own experience is limited to my activities as Chairman of the Central London Railway. I had designed the system, including the power station, and had advised in its operation for some years, but after becoming Chairman, I had to see through two strikes, one a general railway strike and the other a general colliery strike. During the general railway strike, the power station, as the heart of the railway, was a special cause of anxiety. In the coal strike, every department of the railway was crippled. To keep the power station supply assured, special efforts, in addition to the usual ones, had to be made. While I have been largely associated with electric power installations, I came to the conclusion that railway managers had enough to do without embarking on that class of business. Further, that the central power undertaking is in a better position to guarantee a supply under all conditions than any railway company can hope to be, and also, owing to the diversity conditions, can supply cheaper. With the question of supply settled, the electrical system of traction is in a stronger operative position than the steam system.

As to the type of locomotive for heavy freight work, with moderate facilities for repair, I should prefer the side-bar type with motors individually replaceable. The maintenance of such a locomotive is small and the time to carry out repairs a minimum. Axle-driven types of either locomotives or motor cars require a higher degree of skill in maintenance and operation.

With reference to the voltage of the overhead conductor system, owing to the small cost of the conductors as compared with the supporting structure there appears small advantage in exceeding 2500 volts. The size of overhead conductor is largely determined by the maximum current required by the individual trains, so that with increasing traffic density the growth is met by increasing the number of substations without reducing the efficiency. In the case of a line 400 miles in length I made a careful study as between 5000 and 2500 volts d-c. overhead conductor pressure, and came to the conclusion that the saving by the higher voltage was too small to affect the general result. In the case of the 2500-volt installation, the motors could be safely worked at full line voltage, which in my judgment is a material advantage in heavy railway working.

I am glad to see evidence in these two papers that a truly commercial spirit is coming into effect in considering railway problems.

Charles P. Kahler: The foregoing discussion was very interesting to me, in that, although some speakers confined their remarks to the narrow limits of systems of electrification, types of locomotives, and other details, the comparative economics of steam and electric railroad operation, which is really the most important part of the problem, received considerable attention. The data and other information given in my paper, *Trunk Line Electrification* furnished a comparison between steam and electric railroad operation, and the paper could hardly be classed as advocating any one system of electrification, although Mr. Armstrong seems to think it does.

Mr. Armstrong states that the electrification costs depend principally upon the locomotives, substations, and trolley and feeder copper, and that the locomotive costs are high in the case of the single-phase system, while the substation and trolley and feeder wire costs are high in the case of the direct-current system. This is approximately true, considering the single-phase commutator motor locomotive alone, but the locomotive cost would not necessarily be so materially different from the direct-current system if the split-phase locomotive, or the mercury vapor rectifier locomotive to which he refers, were used.

Mr. Armstrong assumes that the substation and trolley and feeder copper costs remain constant as the traffic increases, while the locomotive costs increase as the traffic increases, and draws the conclusion that, even though the single-phase system proves most economical with moderate traffic, as far as first cost is concerned, the direct-current system will, when considered with a 50 per cent or 100 per cent traffic increase, be most economical. Mr. Wynne mentioned two electrically operated railroads where the substation and copper line costs have been materially increased by an increase in traffic, which shows the incorrectness of Mr. Armstrong's premises, and as a consequence, makes his conclusions wrong.

Very few railroad improvements involving any large sums are made without a thorough investigation by the railroad officials of the effect of increasing the traffic. Practically none of the important line or grade changes with which I have been connected were made without considering the effect of at least doubling the traffic. In our investigations of steam railroad electrification, we have gone still further, and besides considering the effect of a change in the volume of traffic have also considered the effect of electrification upon the whole railroad, rather than confining our studies to isolated sections. As a result of numerous studies of this character, I am inclined to believe that electrical engineers, who are usually unacquainted with actual steam railroad operating conditions, would be very much slower in advocating thier own particular fancies if their effect on the whole system was first considered.

The substation and feeder copper cost for a direct-current system which would be of sufficient capacity to permit the operating of trains under such close headway as would be possible on a steam-operated railroad during a congestion or other emergency, would usually be so great as to make electrification unwarranted for many years. As is generally known, the electric distribution system of a direct-current line is not generally designed for any possible emergency, but an allowance is only made for a reasonable contingency, which often is determined by electrical men not familiar with steam railroad operation. On the other hand, it would be commercially possible with a high-voltage trolley, such as is used on single-phase systems, to provide a distribution system which could expeditiously handle almost any congestion or emergency which a steam-operated railroad could.

The development of the mercury arc rectifier locomotive, of which Mr. Armstrong speaks, will no doubt be welcomed by all interested in heavy electric traction work, since direct-current locomotives—which are preferred by Mr. Armstrong and other advocates—can, through the mercury arc rectifier, be made to operate by current from a single-phase trolley. If this new locomotive serves no other purpose than the settlement of the system question, it will have done good service.

The introduction of the mercury vapor rectifier locomotive, together with the split-phase locomotive, which can also be operated from a single-phase trolley, would indicate that the single-phase system, besides providing low cost substations and low cost distribution system, has a further advantage in being adaptable to four or five different types of locomotives.

Mr. Babcock's remarks about inaccurate conclusions being liable to result from generalizing are hardly in accord with his criticism of load factor. He compares his estimated load factor for the proposed electrification of the Southern Pacific lines over the mountain ranges surrounding the Central California valley—which are short in length and where the average grades are heavy—with a long line of railroad with light average grades. It would require about a day and a half for freight trains to cover the 468 miles of line and the stopping or starting of a train at either end of the line would not make a large increase or decrease in the total load, as there would be so many more trains in simultaneous operation on the line, which would not be the case with the shorter line where only a few hours were required to make the run. In fact, the daily load factor would be very high for the longer line.

The California lines have to contend with the heavy freight traffic during the fruit season, whereas on the 468-mile line discussed in my paper the peak of the west-bound business, of which coal forms a considerable portion, does not happen at the same season as the peak of the east-bound traffic, of which lumber forms a large proportion. Also, the maximum passenger traffic

does not occur at the same time as either the peak of the eastward or westward freight traffic. The above, I believe, shows why it is possible to get an annual load factor of 60 per cent for the 468-mile line and only 20 per cent for the short mountain lines to which Mr. Babcock refers.

I cannot check Mr. Babcock's statement that the purchase of electric power at a greater rate than 5 mills per kw-hr. would be utterly prohibited where oil is selling at from 70 cents to 80 cents per barrel. Three barrels of oil are equivalent to one ton of coal, allowing for the higher efficiency of the oil-burning power plant, which would be equivalent to coal at from $2.10 to $2.40 per ton. With a load factor of 20 per cent, the fuel cost alone would not be far below 5 mills per kw-hr., and when the fixed charges and the other operating expenses were added a rate of 5 mills would appear to me low, especially as nothing was allowed for freight on oil or additional charges for transmission lines in case the power plant is built near the oil fields.

Hydroelectric power is at present being sold at as low a rate as the above in many sections of the West. I quoted in my paper the rate of 5.36 mills per kw-hr. which the Great Falls Power Company has given the Chicago, Milwaukee & St. Paul R.R. Also in some sections of southern Idaho power for heating and irrigation pumping is obtained at even lower cost.

Mr. Carter doubts the practicability of making a reduction in the number of freight trains, for traffic reasons, even though the electric locomotives can haul heavier freight trains. Without going into any technical discussion, I would advise that a number of Mikado locomotives, whose tractive power is about 15 per cent greater than the consolidated locomotives, has lately been put in operation on one of the engine districts of the 468-mile line, and an actual reduction in the number of freight trains has resulted. Further, on another division, where conditions were somewhat similar, the train weights were increased by reducing the grades, resulting in a material reduction in the number of freight trains.

For English conditions, Mr. Carter gives the average freight train weights at 60 per cent of the maximum. The figure of 80 per cent given for the 468-mile line considered in my paper was not assumed but was an actual record. This has been increased to 86 per cent for the fiscal year ending June 30, 1913, being 91 per cent for west-bound trains and 82 per cent for east-bound trains.

The possibility of handling the given freight tonnage with only 43 electric freight locomotives has also been questioned, although Mr. Carter qualifies his remarks with the statement that if this can be done it is a pretty sure sign that the line is congested. While this is true, the congestion is partly caused by the equipment troubles on the two helper districts near terminal No. 2.

The train sheet in Fig. 3 was for the day of maximum traffic. Of the freight trains shown, only two are scheduled, the re-

mainder being run as extra. This maximum day train sheet shows that only six freight trains were in simultaneous operation on engine district No. 1, six on district No. 2 and seven on district No. 3, a total of 19 freight trains, requiring 19 freight road locomotives. Additional locomotives would, of course, have to be allowed to provide for helper locomotives, time in enginehouse, shops, etc., but it should be remembered that at the time of maximum demand there would generally be a minimum number of locomotives in the enginehouse. As stated in the paper, the number of electric freight locmotives required is based upon the number of steam locomotives actually used to handle the traffic, allowing for the reduction in the number of freight trains by electric operation and the fact that an electric locomotive is nearly always ready for service and needs to spend little time in the enginehouse. I judge my estimate of 43 electric freight locomotives not only to be large enough to handle the given tonnage but also to provide a larger margin than is usually allowed for steam service.

With regard to the number of electric passenger locomotives, it should be mentioned that of the the three through passenger trains each way per day shown, one is really a solid mail train. No extra mail trains are operated and the number of passenger trains operated in addition to the two through passenger trains scheduled is small, which will account for the apparent narrow margin allowed in the number of electric passenger locomotives. Further, it was proposed to make districts Nos. 1 and 2 one passenger run, there being no objection to this on account of grades or a 16-hour labor law, as would be the case with freight trains. This practise of making the passenger runs double the freight runs is now being followed on some districts with steam locomotives.

In the case of local passenger traffic, the volume is not so uniform as the through traffic, on account of state and county fairs and other things requiring excursion and extra trains, but 14 motor cars were allowed for this purpose. Most of these local extra trains are operated on the west end of the line and the extra cars allowed can be held in readiness at terminal No. 2.

Possibly Table VI, in regard to number of trains, as compiled, should have some explanation to make things clear. The figures shown under the maximum day column mean the total number of trains on the maximum day. The maximum day of passenger traffic does not happen at the same season of the year as maximum freight traffic, as stated, and although the 16 freight trains shown under the maximum day column of district No. 1 are the maximum number, the 10 passenger trains shown in the same column are not the maximum number of passenger trains operated but only the number operated on the maximum day for both passenger and freight traffic. The total number of trains per day, 26 as shown for district No. 1, is, of course, the maximum number for the year. The same applies to the other districts.

The number of passenger trains in the average day column is given in round numbers to simplify computations, the actual figures being 10.5 passenger trains for district No. 1; 8.2 trains for district No. 2 and 8.1 trains for district No. 3, the extra trains being principally local trains. Since the number of passenger trains was taken the same for both steam and electric operation, this would not materially affect the results, which would not be the case for freight service, and the exact freight train figures had to be used.

Although some direct-current locomotive repair costs were quoted in my paper, the electric locomotive repair costs used in the estimates were based upon a study of the comparative repair expenses of the different parts of steam and single-phase electric locomotives, as outlined on page 1217, which shows that it was estimated that a single-phase locomotive would cost about 45 per cent as much as a steam locomotive for repairs. For the direct-current locomotive costs quoted, this figure gets as low as 36.5 per cent, showing that an allowance was made for the relative cost of alternating-current and direct-current locomotives.

The foregoing answers most of the questions put by Messrs. Hall and Welsh. The estimated cost of the steel tower transmission line was based upon the actual cost of a steel tower line lately built parallel to the railroad, the material being distributed by work trains on the railroad, and, if anything, is high.

Catenary construction was, of course, proposed for the high-voltage trolley line. The figures quoted by Messrs. Hall and Welsh appear high even for California conditions, or else they include the cost of the copper trolley.

A number of Mr. Murray's remarks are worthy of careful consideration, especially as he does not underestimate the steam locomotive. He believes that in making comparisons between steam and electric operation of railroads some consideration should be given to the improvement of the steam service, and there is no question but that more consideration will be given to steam railroad electrification by both operating and financial railroad men if the matter is presented in this way. For instance, steam operation of the 468-mile line discussed in my paper could be improved by the use of Mikado locomotives for freight service instead of consolidated locomotives, and by revising both the ruling and helper grades. However, this would take very nearly as much money as required for electrification and the reduction in operating expenses would not, with the present traffic, pay the fixed charges on the investment, while by electric operation a fair return would be had on the investment.

The numerous advantages of substituting electric power for steam on mountain grades, mentioned by Mr. Hill and Mr. Merriell, are generally conceded even by many steam railroad men, and are in accord with investigations made of mountain grades on our lines. Mr. Babcock seems the only one unable to make any showing for electrification on mountain grades.

Our investigations would also indicate that many engine districts of only moderate grades could be more economically operated by electric power than by steam, and in some instances show up better than even the mountain sections; the reason being that on some moderate grade sections the number of freight trains can be very much reduced by electric operation on account of the characteristic of the electric locomotive to operate at overload for short periods. On mountain grade sections, however, the continuous rating of the motors is more important, and although some reduction can generally be made in the train service, it is not as great as can often be made on some moderate grade engine district where the ruling grades are short.

Roger T. Smith (by letter): Mr. Kahler's paper is interesting to English electrical engineers from the complete method of analysis adopted. The examples taken do not, however, invite criticism either of the constants or of the results, since they are not comparable with anything in the way of steam or electric traction that we have or are likely to have in England.

Mr. Hobart's paper, while of course taking its examples from American practise, deals largely with certain fundamental constants for both steam and electric traction common to all railways. The method of analysis used and its lucid presentation conceal the great amount of work which must have been done in the preparation of the paper, nevertheless certain of the constants used in the calculation can only be considered as a first approximation. It may be useful to compare some of them with similar figures taken from English experience, and through the kindness of Mr. G. J. Churchward, locomotive, carriage and wagon superintendent of the Great Western Railway, England, I am enabled to consider several of the constants used by Mr. Hobart in the light of English experience on the longest English railway. While confirming or criticising Mr. Hobart's constants, it is to be remembered that the English figures put forward are for conditions for the most part very different from those in America. Without Mr. Churchward's help no steam figures could have been given, but even these figures are also only to be looked upon as approximations, and Mr. Churchward must not in any way be held responsible for the manner in which the figures are presented.

Page.	Line.	Constant or Assumption.	Deduction affected by assumption.
A.	B.	C.	D.
1151.	29.	Coefficient of adhesion, 0.20.	Maximum available tractive effort.
1152.	6.	Average tractive effort over 100 miles for both loco. and load 9 lb. (10 lb.) per ton at average speed 50 mi. per hr.	The whole subsequent investigation depends on this figure.

Mr. Hobart deals first with steam and electric constants for a fast passenger service covering 100 miles in two hours.

Steam figures are given for a Pacific 4-6-2 type locomotive. The difference between the American ton and English ton may easily result in considerable confusion in comparing constants used in the two countries, and while my figures are all given in American tons of 2000 lb., the equivalent in English tons of 2240 lb. will be given enclosed in brackets. The author's engine weighs 115 tons (103) with 85 tons (76) adhesive weight, hauling a train of 750 tons (670). The comparative figures will for the most part represent results obtained with 4-6-0 type engines having a weight of 85 tons (76) with 62 tons ($55\frac{1}{2}$) adhesive weight, hauling passenger trains rarely exceeding half the weight of the American train.

The value of the coefficient of adhesion should not be taken as higher than 0.20. Experience with trains of about half the weight of the author's train gives 9 lb. train resistance per American ton (10 lb.) as a good average figure. Sufficient data are not available to determine whether the tractive effort is the same for the locomotive as for the coaches but it is to be remembered that this confirmation of the author's figures applies only to the coaches. There is reason to believe that train resistance is greater for the locomotive, and there is considerable advantage in dealing only with drawbar forces, such as can be measured on a dynamometer car, rather than with forces in the cylinder, the measurement of which by means of the indicator is extraordinarily difficult and liable to many errors.

A.	B.	C.	D.
1152.	9.	Efficiency from cylinder to crank pin, 85 per cent.	The average i.h.p. required throughout the journey, the coal burnt and the journey efficiency.

This efficiency would be more satisfactory if stated as between cylinders and rims of driving wheels. While curves of drawbar h.p. plotted with speed under specific conditions can be readily drawn to connect many points determined experimentally, the corresponding i.h.p. values are very hard to connect by a smooth curve. An average value of ratio $\frac{\text{drawbar h.p.}}{\text{i.h.p.}}$ may be taken to be 70 per cent, and the indicated h.p. under the author's conditions would on this assumption be 1290 instead of 1320, thus checking the value of 85 per cent very closely.

A.	B.	C.	D.
1152.	14.	Coal per i.h.p. = 3.5 lb. of calorific value of 14,000 B.t.u. per lb.	The coal burnt and the journey efficiencies from coal to cylinder and to wheel rims.

On trials where the ratio $\frac{\text{d-b. h. p.}}{\text{i. h. p.}}$ was 0.70 the pounds of Welsh coal of a calorific value of 15,400 B.t.u. per i.h.p. were 2.75, which would probably correspond to 3 lb. per i.h.p. for the author's lower calorific value. Taking the actual figure of 2.75 lb. for the better coal the journey efficiency from coal to drawbar is increased from 3.53 to 4.1 per cent.

A.	B.	C.	D.
1153.	17.	Coal used for firing up and at end of journey 3000 lb. or 32½ per cent of coal used on 100 mile run.	Affects the reduction of journey efficiency from coal to drawbar.

The figure 3000 lb. for the coal used for firing up and at end of journey would be considered very exceptional. About 800 lb. for firing up and 1100 lb. left in the firebox at the journey's end may be considered as representative figures for the largest English engines. This added to the coal used on the run would reduce the journey efficiency of coal to drawbar from 4.1 per cent to 3.2 per cent as compared with the author's figure of 2.85 per cent, the coal per drawbar h.p. amounting to 5.2 lb. instead of 6.86 lb.

For the electric locomotives, if we accept the author's assumption that the resistance per ton of locomotive is the same as for the coaches, and the other carefully prepared and fair chain of efficiencies between the coal bunkers and the rims of the drivers given on pages 1154 and 1156, the final figure for this efficiency given by the author is 6½ per cent. With the steam figures already given for an English railway with locomotive coal of 15,400 B.t.u. or 6 h.p-hr. per lb., 57 per cent of the coal used by the steam locomotives would be required to haul the train electrically, as compared with the author's 47 per cent.

If steam locomotive working costs include coal, water, running wages and superintendence, lubricants, small stores, and locomotive repairs and renewals, the average cost of working a locomotive—that is, the total of these costs divided by the total number of locomotives in service—is about \$5000 per annum.

Of these costs, coal and water account for about one third. It is suggested that these total costs, averaged over the whole stock, and then modified to suit each type of locomotive for which the average consumption of coal per mile is known, would be the most useful figure for comparison between steam and electric locomotives. I regret not to be in a position to give this analysis for different types.

In comparing steam and electric locomotives for fast passenger service it must not be forgotten that, with increasing speed, the series motor falls off in output much more rapidly

than the steam cylinder. The type of English steam locomotive most in favor for fast passenger service can give a measured (not calculated) drawbar h.p. of 1100 at 70 miles per hour. The Pacific type could of course give a greater h.p. Have any electric locomotives in America given a measured drawbar pull of 5900 lb. at 70 miles per hour?

Agreeing with all that the author has said as to the purchase of electricity in preference to its generation by the railway, the British system of small municipal electric supplies in each town militates against the price of electricity offered by the large power companies falling to a sufficiently low figure except on the N. E. coast, where attractive prices are offered for traction. This has an important bearing in connection with the type of traffic dealt with in the second part of Mr. Hobart's paper under the head of "Mountain grade railways," where the hauling of heavy goods trains is considered firstly up 0.3 per cent grades and secondly up 1.5 per cent grades.

Here again our conditions are different. There are probably 700,000 privately owned traders' wagons in the United Kingdom for which the drawgear is, when new, tested to 56 tons (50). This permits of a maximum tractive effort of 13½ tons (12) and a maximum starting effort of 19 tons (17), and no locomotive giving more drawbar pull than this is required for general use. But apart from the loss of strength by wear, a considerable percentage of traders' wagons are much below this standard and in general make very heavy freight trains impossible. On some railways and in some classes of mineral traffic the company's own wagons are solely used and in such cases drawgear can be suited to heavier trains, but there is no difficulty in building, within the British load gage, steam locomotives (such for instance as those of the 2-8-0 Consolidation tank type with 70 tons (62½ tons) adhesive weight) capable of pulling the heaviest trains containing traders' wagons which from the strength of their drawgear it is safe to marshal. In this country, therefore, save in some special cases, the advantage of hauling heavier goods trains than can be hauled by a steam locomotive does not exist. In spite of this, the electric hauling of heavy goods trains in hilly districts is, after suburban passenger traffic, the most promising field for electric traction in this country, on account of increase in possible speed.

Let us turn again to the author's constants, remembering the British drawgear limitation in the possible maximum weight of goods trains in general.

A.	B.	C.	D.
1163.	19.	Total resistance of trailing load at 14 mi. per hr. = 4 lb. (4.5) per ton of loaded train, and 8 lb. (9) per ton of empty train, both at 14 mi. per hr.	The drawbar h.p. and all subsequent results.

Different load conditions in the two countries make comparisons difficult. For a 560-ton (500) train the resistance per American ton was 6 lb. (6.7) and for the empties weighing 215 tons (190) the resistance per American ton was 15.1 lb. (15.9), but the speed was 20 miles per hour instead of 14 miles. The value 560 tons, approaches the possible British limit of train weight with a ruling gradient of 1 per cent.

A.	B.	C.	D.
1164.	2.	Starting adhesion from 25 per cent to 30 per cent.	The maximum starting effort of locomotive.

The adhesion at starting with the 2-8-0 type of goods engine is 0.32.

No useful comparison can be made with English conditions, of the various constants leading to the efficiency for mountain grade locomotives between the coal and the drawbar. The amount of 30 per cent added for the coal used when the locomotive is standing can, however, be confirmed.

It is not possible to give a figure comparable with the author's figure for locomotive repairs. It is presumed that the figure of 10 cents per mile per 100 tons is an average figure and that for the Mallet locomotive under consideration it would be more.

Only one other figure used in the author's interesting comparisons between steam and electric locomotives on mountain grades can be given from experience this side, and that is with reference to the 16,000 traffic miles per annum of the Mallet locomotive. On a Welsh section including a ruling gradient for 2 miles of 2.0 per cent the average annual mileage of the 2-8-0 type of locomotive is 15,000.

It is a misfortune that the type of goods service in hilly districts for which ele ctric traction is most suited in England is conducted under such very different conditions from those obtaining in America that a comparison with the author's figures is only possible in one or two instances. Such comparisons as have been made point to the close agreement of the author's constants with those obtained from one English railway.

H. M. Hobart (by letter): The more valuable portions of the discussions of the papers by Mr. Kahler and myself consisted in written contributions containing a large amount of quantitative data which required detailed analysis in order to disclose its significance. Indeed, the significance of the contributions of Messrs. Babcock, Hall and Welsh have only become clearly apparent after studying them in conjunction with Mr. Babcock's paper entitled *Mountain Railway Electrification*, which is published in this volume of the TRANSACTIONS, page 1845. In this paper Mr. Babcock considers a mountain railway which in many respects is practically identical with the case which I worked out in my paper, and it is only recently that I have been able

to study all this material. This study has satisfied me that Mr. Babcock may be in error in extending his unfavorable conclusion as regards electrification of mountain railways to cases where the conditions are less favorable with respect to low cost of fuel, than in the exceptional case which he has considered. Mr. Babcock has based his steam locomotive costs on the use of oil purchased at about one cent per gallon or 42 cents per barrel. Oil fuel at such a price is equivalent to lignite (of a calorific value of 11,000 B.t.u. per pound) at a price of $1.60 per ton. For my example of a 96-mile mountain-grade railway I assumed a price of $2.40 per ton. This price is the lowest which could be considered representative. I devoted a page of my paper to pointing out and emphasizing the fact that with decreasing price of fuel the case for electrification rapidly became less favorable. The substitution of $1.60 per ton for fuel in place of my figure of $2.40 per ton would have greatly decreased the margin in favor of electrification.

It will be agreed that the price of about one cent per gallon (42 cents per barrel) for oil fuel is local in its application. At a price of 2 cents per gallon (84 cents per barrel) the item of $241,000 for locomotive fuel in Mr. Babcock's paper becomes $482,000 and increases his "Steam" total of $687,000 to $928,000. Furthermore, Mr. Babcock gives items for first cost of (I) Substations and (II) Contact System and Bonding, of $1,610,000 and $1,100,000 respectively, or a total of (I) and (II) amounting to $2,710,000. The output of the substations amounts to only some 47 million kw-hr. per annum. For a load of the character handled on his railway the substation outlay could certainly be reduced to much less than half of his figure. Without going at length into this matter, (which appears to be the chief point of difference between our estimates), I should unhesitatingly reduce Mr. Babcock's $2,710,000 by $800,000. Bond interest at $4\frac{1}{2}$ per cent comes to

$$0.045 \times 800,000 = \$36,000.$$

and when subtracted from the "Electric" total of $451,000, leaves....................................$415,000.

We now have

Steam..................................	$928,000
Electric..................................	415,000
Difference..................................	$513,000

from which the cost of the electricity is to be defrayed. 55 million kw-hr. delivered annually to the substations at a price of 0.65 cents per kw-hr. amounts to an annual charge of $358,000, leaving a balance of $155,000 to cover taxes and depreciation. The net investment is

$$\$3,828,000 - \$800,000 = \$3,028,000$$

of which amount our $155,000 is 5.1 per cent.

This is a conservatively prepared statement and is interesting in disclosing (1) the effect of the fuel cost on the result and (2) the influence of the substation arrangements.

I cannot agree with Mr. Babcock's optimistic estimates of the efficiency in his electric alternative and in a close analysis corrections ought to be introduced in this respect which would render the results a little less favorable to electrification. On the other hand, I have taken no account of the decreased outlay for substation labor and supplies which would ensue from halving the number of substations and eliminating the feature of starting up the machinery just prior to the approach of each train.

If my results indicate the general order of magnitude of the investment and operating costs, it would appear that the increased capacity consequent upon the electrification of such a mountain grade railway should be amply attractive to justify serious consideration of electrification on the part of the executives of such roads.

Mr. Roger Smith's contribution contains data of very great value. Engineers will appreciate having available the precise figures which Mr. Smith, the chief electrical engineer, and Mr. G. J. Churchward, locomotive superintendent, of the Great Western Railway of England, have here presented. The Great Western data closely confirm my assumptions and in so far as they deviate therefrom will be of valuable guidance in arriving at more appropriate assumptions in investigations of this sort.

I accept Mr. F. W. Carter's suggestions as very much to the point. Mr. F. C. Merriell alludes to the important superiority of electrical operation as regards immunity from the difficulties attending steam-locomotive traction in extreme cold weather. The point is one of much importance.

With reference to the discussion of steel rectifiers by Messrs. Armstrong and Murray, I should like to refer to pages 136 and 137 of a paper entitled *The Relative Costs and Operating Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems*,* in which I called attention to the useful and useless lines on which such apparatus may be developed. If Mr. Murray will refer to that paper and to his own experiences he will see that there is need for a revision of his statement that "the power houses of the single-phase and continuous-current systems are about a stand-off." Mr. Parshall expresses the opinion that the paper credits the steam locomotive with a better performance than is representative. The criticisms of Messrs. Murray and Wynne, on the contrary, appear to be to the general effect that I have underestimated the performance of the steam locomotive.

It is interesting to contrast the conclusions of Mr. George Hill with those of Mr. Babcock. The former states that his

*Trans. A. I. E. E., Vol. XXXI, (1912), p. 115.

firm has satisfied itself in the course of its investigations that electrification will make a very satisfactory showing for many cases of heavy mountain grades: the latter has reported on "every mountain railway exit from the Central California valleys, and on other mountain districts in other parts of the West Coast country" and the conclusions have invariably been adverse to electrification.

Mr. Wynne criticises my 78 per cent annual substation efficiency for the mountain-grade service as being too high, and recommends that it be decreased by from 7 to 10 per cent. In Mr. Babcock's paper the annual substation efficiency is taken as 90 per cent. In my opinion this is 10 per cent higher than he could obtain by any practical means for the service he describes. In Mr. Wynne's opinion Mr. Babcock's figure is 20 per cent too high.

I am especially glad to have the data which Messrs. Hall and Welsh give relating to the cost of Mallet locomotives. Although the figures which I obtained for the cost of Mallets were from very reliable sources, nevertheless, I should have employed somewhat lower prices had these further data been known to me. The comparative result would, however, not be much affected, if at the same time, I had taken the electric freight locomotives at $350 per ton, the figure employed by Mr. Babcock in his paper, in place of the figure of $450 per ton which I employed for the electric locomotives in my estimates.

A. B. Babcock (by letter): Mr. Hobart is satisfied "that Mr. Babcock may be in error in extending his unfavorable conclusions as regards electrification of mountain railways to cases where the conditions are less favorable with respect to the low cost of fuel than in the exceptional case which he has considered." It seems impossible for me to make plain enough to be understood that my conclusions are not unfavorable to electrification of any railways, mountain or plain, except those that I have investigated personally and reported on adversely. While these concern the exits from the Central California valleys, and some other mountain districts on the West Coast, there are many other districts in which electrification may be extremely profitable. I am not aware that I have ever made a statement favorable or unfavorable to electrification in general.

Mr. Hobart, if I understand his argument, goes on to assume a hypothetical value of fuel and from that argues himself into a position contrary to that resulting from my analysis of the Tehachapi figures. With reference to this, permit me to call his attention to my discussion of his paper (see page 1237, preceding). "While in the hypothetical case, from a given set of assumptions one may argue himself into almost any desired position, in practise the hard and unyielding physical facts are met." He also states, "For a load of the character handled on his railway the substation outlay could certainly be reduced to much less than half his figure." Again permit me to

call his attention to the fact that actualities are considered in my Tehachapi paper and to refer him to the paragraph wherein I said, "This traffic must be handled as circumstances require. It cannot be spaced conveniently for power demands, as many engineers and power men have suggested, but the terminal yards must be cleared as the cars accumulate."

Mr. Hobart contrasts the conclusions of Mr. George Hill with mine. Mr. Hill's viewpoint and mine are different. Again I will refer him to my Tehachapi paper, first and third paragraphs thereof.

From the foregoing quotations it would appear to me that Mr. Hobart has not read the Tehachapi paper with the care that would justify his positive statements with reference to my attitude. For his information I will state that the said Tehachapi paper was written in the hope that it would draw out a discussion wherein, if my office has been in error for the last ten years with respect to such problems, these errors would now be pointed out by those who are competent to have opinions on this subject. So far only Mr. Hobart has offered a criticism. He appears to have read it without discovering that it deals with facts,—with things as they are, not with things as both he and I might wish to have them. Only a few weeks ago I stated to a representative of a prominent engineering firm that I would be very glad to be shown that my conclusions are erroneous, if such is the fact, and I made the offer at that time, which offer still stands open, that although I had stated in the Tehachapi paper the absolute operating facts as taken from the company's records, I am ready at any time to turn over to competent members of any of the large electrical manufacturing companies, all of the operating data that can possibly cast light on these problems, to give them access to all of the facts in connection with the property, and if they can convince our operating officials that there is a profit in the electrification of any one of the mountain outlets from Central California, as operated by this company, or as can be reasonably operated by this company, I stand ready to confess my error as publicly as I have stated my conclusions; but I will neither take part in general discussions that lead nowhere, nor will I pick up straw men after they have been knocked down.

An address presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

SOME ASPECTS OF INSTITUTE AFFAIRS

PRESIDENT'S ADDRESS

BY RALPH D. MERSHON

The address of the retiring President of the Institute has usually dealt with some aspect of engineering, or with the engineer. It has been the exception, rather than the rule, that a presidential address has discussed Institute affairs. It seems to me eminently fitting and desirable that in retiring from office, the President should record his views on the more important matters affecting the interests of the Institute, with which he has become acquainted as the result of his administration, and the years of service that preceded it. It is my purpose, therefore, to discuss some of the more important problems confronting the Institute, and record my views on them, and on some of the general conditions affecting the welfare of our organization.

All of us, I am sure, desire that the intensity and scope of the activities of the Institute shall continually increase. That new technical committees shall be instituted, as fast as the progress of the art of electrical engineering justifies them. That new Sections shall be formed. That Institute meetings, or Conventions, under the auspices of the Sections, shall be held whenever a Section desiring such a meeting can justify its authorization. In fact, that Institute affairs shall always be so conducted as to best conduce to the progress of the art with which our organization concerns itself. But there is a limitation on the degree of such activities, quite aside from the willingness of the individual members to give the time and energy necessary for them; the limitation imposed by the relation between income and expenditures. Take, for instance, the matter of technical com-

mittees. Whenever a new technical committee is formed it means added expense, principally for printing. It means, under our present method of procedure, that the matter resulting from the activities of the new committee will be issued to each of our 7500 members. It will be issued to each of them twice; once in the PROCEEDINGS and once in the TRANSACTIONS. The increased expense incident to the addition of a particularly active technical committee may, therefore, be quite a considerable item. It is evident that our activities, through technical committees, or otherwise, might be stimulated to a point where our income would not be sufficient to meet expenses. The Institute is approaching such a condition of affairs. The amount of our annual expense is uncomfortably near to that of our annual income. We must, in the near future, either slow down in the rate of increase of our activities, or cut down our expenses, or increase our income. We must either make our activities keep pace with our increase of membership, or decrease the expenses of our activities, or raise our dues. The last course would be highly objectionable, and the first highly undesirable. The second expedient, that of cutting down our expenses, is the only one that appeals to me. I believe it to be feasible, and I am sustained in this opinion by those of our members with whom I have discussed the subject.

Our largest single item of expense is printing. Undoubtedly we spend a good deal more for printing than is justified. From time to time we print papers and discussions whose proper medium is the technical journals, not the Institute publications. Our printing and mailing expenses can be considerably reduced by a more searchingly judicious selection of the matter for publication from the wealth of matter presented before the Institute. They can be much further reduced by devising some scheme whereby each member will receive only that matter which deals with the subjects in which he is interested, with the proviso that he can receive all the matter issued by paying something in addition to his regular annual dues. Possibly, also, we can avoid sending out the same matter twice. Undoubtedly there can be, and should be, devised some expedient, whether along the lines suggested or otherwise, that will be acceptable to the membership and will result in a saving which, for a time at least, will push forward the expense limitation upon the increase of our activities. The membership should assist the governing body in solving this problem.

This question of expense has a bearing, not always clearly appreciated, upon another matter. We often hear expressions of regret that other societies have been formed to deal with subjects presumably falling within the scope of the Institute. But I question whether this is always, or ever, a proper subject of regret.

If a new society be formed some of its members will be men who are also members of the Institute. These members, common to both societies, will pay into the new society dues in addition to those they pay into the Institute. Also, the new society will send out its publications to its own limited number of members.

If the new society be not formed, if the Institute takes up the work, that the new society would cover, with the same degree of intensity that the new society would, the Institute will do this without any proportional increase of income, and will, under our present scheme, send the publication of the new matter to all the Institute members, instead of to the comparatively few of the new society. If it is true that the expense *per member* of the Institute for issuing this matter will probably be less than in the new society, it will not be enough less to counterbalance the fact that the Institute will have no proportionate increase of income, due to the new activity, and to the fact that the published matter will be sent to all the Institute members instead of the smaller number of the new society.

It appears, then, that a new society accomplishes for the art of engineering, generally, two of the possible expedients mentioned above in connection with the Institute. That is, it increases the total income available for technical work, and keeps down the gross expense by sending published matter to those only who are interested in it. It would appear, therefore, that the splitting off of a new society from the Institute is not an unmixed evil. Perhaps there is, and in many cases I think there is, no evil in it at all. Of the members of the new society who are not members of the Institute also, few, if any, would have been members of the Institute if the new society had not been formed, and such additional members as might have been attracted to the Institute by reason of the new activity would not have yielded an increase of income comparable to the increased expense. On the other hand, the formation of the new society will draw away from the Institute few, if any, of its members.

Similar considerations apply to the question of amalgamating engineering societies, of which we hear from time to time. If

engineering societies were brought together in a very general organization of the nature of a holding company, possibly some considerable benefit might be derived therefrom. But if they were to be actually amalgamated into one society, I think it very questionable whether the disadvantages would not greatly outweigh the advantages of such a course.

For a good while there has been a tendency based upon tradition and precedent, to limit the scope of the Institute's work to those merely technical activities which some people seem to think constitute the sum and substance of engineering work. The attitude has been that the engineer is not concerned with dollars; that it is beneath his dignity to deal with them. This attitude has been maintained in the face of the fact that in all important practical engineering work the question of dollars is the very first one involved, whether it be in the construction cost of the work, in the operating expense in connection with it after it has been installed, in the profit to be derived from its operation, or all of these. I believe it is becoming more and more clearly realized that this old point of view is not only narrow, but erroneous; that a technical man is not an engineer unless he is an economist, and that he can not be an economist unless he can, and does, deal with the dollar side of every engineering proposition. This more enlightened point of view is being reflected in the work of the Institute, as is evidenced by the appointment of committees to deal with such things as depreciation, operating costs, etc. It is to be hoped that this tendency towards the liberalization of Institute activities will increase.

The system of local Sections, which has now been in operation in the Institute for ten years, has grown in importance and value, and will undoubtedly continue to do so as time goes on. I consider that some of the most valuable work of the Institute is being done because of the existence of the local Sections and I believe the importance and the value of the work done because of, and due to, the Sections will continually increase. I say this the more gladly because at its inception, and for some time afterwards, I took an unfavorable view of the Section movement, and had grave doubts as to the possibility of the Sections ever amounting to much.

It has been suggested that the Sections be encouraged to make their organizations more formal than at the present time. That they have a system of technical committees corresponding to the technical committees of the national organization, in so far as the subjects with which the national committees deal are of

interest in the part of the country in which the Section is located. It has also been proposed that where a Section has a technical committee dealing with a given subject, the chairman of the committee shall be a member of the corresponding national committee. These suggestions are, it seems to me, worthy of careful consideration. Their adoption would be a means of more closely binding together and correlating the technical work of the national body with that of the several Sections. I have, during the past year, endeavored to realize some of the advantages of such a scheme by appointing to committees men recommended thereto, at my request, by the Sections. The adoption of the suggested interlocking committee scheme would more or less automatically take care of the matter.

But whether the idea of similar technical committees be carried out to the extent suggested or not, it seems to me exceedingly desirable that each Section have a Membership Committee corresponding to the Membership Committee of the national organization. And that hereafter any effort made to acquire members be exercised, not by the Membership Committee of the national organization directly, but by that committee through the several membership committees of the Sections. It seems to me hardly in keeping with the dignity of the Institute to circularize for members. If each Section has a Membership Committee, these local committees will be in a position to campaign for new members, either by direct personal contact, or by enlisting the aid of other members of the Section, who, by personal contact and influence, can bring about the desired end much more effectively than it can be accomplished by means of circulars; and certainly in a manner much more compatible with the dignity of the Institute.

It is desirable that the membership generally take a greater interest in the conduct of Institute affairs, and participate in such conduct, so far as geographical location will permit. Many of the problems arising in connection with the work of the Institute can best be solved with the aid of our members, and they should not only be encouraged but expected to lend this aid. Such general participation would undoubtedly be facilitated if there were a better geographical representation on the Board of Directors than there has been in the past. While I realize that the greater number of the Directors must be drawn from sections of the country from which Institute headquarters are easily accessible, in order that the work of the governing body shall not be hampered, yet it is desirable that a certain number

of the Vice-Presidents and Managers be distributed over the remainder of the country. This could be done, without running the risk of seriously hampering the work of the governing body, if that body were increased by the number of the members to be apportioned to the districts more remote from headquarters. It seems to me that such increase and apportionment is desirable, not only as a means of participation, but as a means recognizing effective service and achievement on the part of members distant from headquarters.

Participation by the members in the conduct of Institute affairs would also be fostered by greater publicity in the matters coming before the Board of Directors. We obviously cannot expect the cooperation of our members, no matter how willing they may be to give of their time and effort, unless they know of the problems on which cooperation, advice, suggestion and criticism are desirable. There has been a tendency to take the attitude that it might be harmful to the Institute if matters on which there were differences of opinion in the Board of Directors became known to the membership. To my mind this is erroneous. I believe no live organization is hurt by discussion, no matter how general it may become. In fact the more open and general discussions are, the more likely is the organization to maintain a healthy condition. If there be vigorous differences of opinion, vigorously expressed, it is an evidence that the organization is alive; and if there be any contention, the more public it is made the more likely it is to be conducted in a spirit of the utmost fairness. For my part, I should much prefer an organization live enough so that its affairs would evoke discussion, than one so dead that no discussion or contention would ever have place. Discussion, constructive criticism, even contention, when it involves matters of principle, are evidences of the vitality and worth-whileness of the organization, and not evidences of disintegration, or any tendency thereto. I believe it much better in every way for the Board of Directors to allow members to know of any considerable differences of opinion that may arise in the Board, than to endeavor to cover them up under the mistaken idea that harm to the Institute may result from their publicity. The Board should have nothing to fear from publicity. If it has anything to fear, that is all the more reason why the members should be apprised of the matter at issue.

Much of the opposition that is at times evidenced in new departures on the part of the Institute, and many of the criticisms

of current courses of procedure, are based on precedent and tradition. While I believe precedent should always be considered, I see no reason why it should not be promptly overruled if contrary to any course that on careful consideration appears advantageous and desirable. Precedent is, it seems to me, mainly valuable as causing us to more carefully consider a course proposed contrary to it, or as the basis for a decision in doubtful questions. The most striking and valuable improvements have almost always come as the result of action directly contrary to all precedent. The criteria of yesterday will not necessarily serve for today; and the criteria of today will probably not all serve tomorrow. There is no more reason why we should necessarily conform to the practise of others, or to our own practise in the past in Institute affairs, than there is in any of the other affairs of life. For instance, society is coming to see the futility and false modesty of endeavoring to blink certain physical facts in connection with human nature. It is coming to realize the false modesty and almost criminality of endeavoring to ignore those things which nature will not permit to be ignored except under penalty, and as a result some matters are now openly discussed with a frankness that would have caused our forbears to hold up their hands in horror. There is no reason, that I can see, why in Institute affairs, any more than in the other affairs of life, we should hesitate to do those things that are obviously both fundamentally right and expedient, no matter what tradition may be outraged, or how contrary such course may be to previous custom and usage.

There have been criticisms of some of the present methods of conducting the affairs of the Institute which I think should be viewed in the light of what I have just said, rather than in the light of precedent. One of these is the matter of anything of the nature of competition for the offices in the gift of the Institute. To my mind a spirit of competition is to be welcomed rather than frowned upon. The offices of the Institute are no sinecure. The officials and others conducting the affairs of the Institute are directly responsible for the results obtained, and in order that effective results shall be forthcoming it is necessary that they devote a considerable amount of time and energy to the work their tenure of office implies. It is a matter of congratulation, therefore, it seems to me, that there should be competition for an opportunity to do hard work. It is evidence of the live condition of the Institute, and of its capability for accomplishing

results. To my mind it is a great deal better both for the Institute and the individual office holder that the latter attain his office as the result of his frankly evidencing his desire for it, and if necessary competing for it, rather than under the fiction, that no one believes, which would make it appear that he is prevailed upon to accept the office only through the urging of his friends.

There has been some objection to the circularizing which has sometimes been resorted to in connection with the election of officers; the idea being that it were better if the nominations were quietly made, by a selected group of men, and the election conducted without any possibility of opposition. In other words, that, in effect, the officers of the Institute should be chosen by a selected few instead of by the membership at large. I have even less patience with this point of view than with that just cited. To put a ban upon circularizing would be to throw the power of nominating and electing into the hands of those who might be in position to control these functions without the necessity of circularizing, by virtue of their ability to avail themselves of organizations outside the Institute, or by their control of organized cliques within the Institute. To forbid circularizing would absolutely tie the hands of those independent of any other organization, or of any clique, and would tend to put a premium on the control of the Institute by oligarchy.

There has at times been evidenced a tendency to elevate to the high offices of the Institute men who have done little, if any, work for the organization. To my mind this not only works an injustice upon those who have given the Institute their best efforts, but is against the best interests of the society in every way, especially if the individual's chief claim to prominence arises from activities in fields other than that of electrical engineering as defined by the Institute's constitution. One of the incentives to effort on the part of the individual members of the Institute is that of the possibility of recognition of such effort through appointment, or election, to some official, or semi-official, position. I am quite aware of the fact that in some quarters this is not admitted, and that such sentiments as this are taboo. But to convince himself that the statement I have made is a true one, one needs only to ask any individual who has labored faithfully for the Institute, whether in case it had been possible for him to have done the work accomplished without the remotest chance of his name ever being known in connection with the results attained, he would have been willing to labor as faithfully for

their attainment. In almost every case, if not every case, an honest answer will compel the statement that he would not.

It is the young man starting into his life work that we especially desire to attract to the Institute. Young men starting the struggle for existence have scant opportunity for devoting themselves to things other than those which will immediately forward their interests. Later on, when a certain amount of success has been achieved, they may indulge in the luxury of altruism, but until such measure of success has come to them they are neither justified in indulging in the kind of altruism that unrequited Institute work implies, nor are they willing to do so. It behooves us, therefore, to make service in the Institute as attractive to them as possible, and to this end we should so guard the offices of the Institute, elective and appointive, that they may be the reward, not only of achievement in electrical engineering, but also of service in the Institute. That the membership will feel that the criterion of fitness for these offices shall be not merely prominence, however great, but also a generous measure of previous effort in forwarding the interests of the Institute and the principles for which it stands.

Remarks similar to those I have made in regard to the Institute offices will apply to the question of membership in the Institute, and preservation of the highest standard for the various grades laid down in our constitution. In discussing the eligibility of candidates for membership whose qualifications do not seem to square with the requirements of our constitution, but who are prominent in some lines other than those covered by our constitutional requirements, those favoring the candidate often make statements as to his great ability and express their belief based thereon that he is entitled to membership. These people lose sight of the fact that the requirements for membership in the Institute are not a question of the opinion or belief of any individual. They lose sight of the fact that the requirements for membership have been agreed upon by the members of the Institute and are laid down in the constitution. The only opportunity, therefore, for opinion or judgment is as to whether the candidate meets these constitutional requirements. If the constitutional requirements are not what they should be, and if the membership comes to the conclusion that they should be other than they are, then they should be changed; but so long as they stand, they, and only they, should be the standard by which to measure eligibility.

I quite realize the fact that from the point of view of a few some of the things I have said not only are unorthodox, but border on heresy. I believe, however, that my views will be concurred in by a large majority of the membership. If they are not, then I cannot expect them to be of any effect or influence. If they are, I sincerely hope they may have an influence on the future course of Institute affairs.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

A SUGGESTION FOR THE ENGINEERING PROFESSION

BY WILLIAM McCLELLAN

The engineer of today traces his ancestry along two distinct lines, one practical, the other theoretical. In times past what we call engineering was done either by a skilled mechanic or by a scientist having a practical bent. As the demand became more and more complex, and as science opened up wider and wider fields of knowledge, the mechanic became more and more skilled in certain ways and some scientists became more and more practical. The merging of these formed a group of workers, having common aims and now known as engineers.

The skilled mechanic, however, from the standpoint of quantity, was by far the larger element. One need go back only to pioneer or colonial days to learn that practically all of the engineering, as we know it, was done by the surveyor, the millwright, the master carpenter, the master mason, the smith, and others. Even now, many a smith claims to be able to forge without plans, a hook equal to any that a mechanical engineer can design, and many a country carpenter will frame quite complex roofs of a variety of types, all "out of his head."

Passing quickly over many interesting details, we find that more or less on account of their industrial lineage, engineers are divided into classes. Once there were two of these, civil and military. Later, starting with the multiplication of engines and machines, the civil class divided up into the almost innumerable varieties of engineers which it is unnecessary to list here—if we could.

As a result, while there are many men of great breadth of mind and experience worthy of the title of "engineer," there

is no one who can claim it in the same way that lawyers and doctors can claim their titles. There are engineering professions, but there is no one profession. There are engineering degrees, but there is no one engineering degree. There is no engineer without an adjective. It must be acknowledged that there is some truth in the charge of "lack of breadth," considering the whole body of engineers. It is also curious that in medicine and law the students leave school all with the same general training and degree, but specialize afterwards, whereas in engineering they are specialists at school.

So far as individual activity is concerned, engineers are of different types in the same way that lawyers and doctors are, but to a greater degree of demarcation. Today all the numerous classes of engineers contain three distinct types of members:

First, the theoretical engineer, who in reality is not an engineer. He is, and it would be proper to call him, an applied scientist. Many of the engineers in our great electrical manufacturing companies are in this class.

Second, the mere manual and mental operative, the hewer of wood and drawer of water in the engineering world.

Third, the real engineer who can design and create, who can adapt the resources of nature efficiently to the service of man.

In passing, it may be remarked that the presence of these three types in each class of engineers is the chief difficulty in arranging proper courses in engineering education.

The intensely practical result of all these causes is that engineering is not securely established as a profession; it is difficult for the engineers of the country to act as a unit where united action would be of benefit to society; the engineer is handicapped in obtaining recognition and authority when working jointly with men of other callings and professions; and finally, on account of its divisions, the development of the profession as a whole is proceeding slowly and inefficiently, resulting in an economic loss to society.

Many will remember how often within the last few years a demonstration or recommendations by a united engineering profession would have been valuable. Society needs such help in connection with conservation discussion, appointments of the many municipal, state and national commissions involving engineering in some form, opposition to ill-advised or vicious laws, methods of conducting public work, and a variety of other similar matters.

When unity is so desirable or even necessary, a great effort is worth while to obtain it, but the question is, how?

We might turn to the colleges and technical schools. I have suggested before, and long to see the time, that some prominent school shall offer the degree of Bachelor of Engineering, and give all such students the same general course with a very small percentage of special electives. The schools are moving in this direction and we should have great faith in them. Of necessity the progress is slow and will not answer immediate needs. If revolutionary changes were possible at once, the effect would not be seriously felt for years. The schoolmen must be given time to work out their plans. Outside engineers may occasionally offer valuable suggestions but they are much less able to attack the problem than those whose business is to study it at close range.

If custom were followed, where it is desirable to get united action in some one direction, a great national society of engineers would be organized to which all properly qualified engineers would be eligible, irrespective of their adjectives. Many men have thought of this, but for a number of reasons it is not practicable. There are a large number of "adjectival" societies now, to which great numbers of engineers have given their allegiance. No one society could be formed without having at least four sections equal in importance and influence to the four great national organizations.

One of the four principal societies having an honorable and distinguished history claims to be such a general society, and its constitution provides for the admission of any engineer having sufficient proficiency in his line. The claim to the title can be only nominally upheld, however, because the connotation of "civil" engineer today is so well known to everyone that it is not even necessary to discuss it.

What then can be done? Unity we need badly—unity we ought to have. I have sometimes thought that if a great organizing genius, such as is discovered occasionally in the industrial world, were to undertake the problem, he might build a merger out of or on top of the present organizations, which would leave them organically intact, but provide for united action in general fields. Engineering might have a federal government. It is to be feared, however, that the time is not ripe. Nevertheless there is every reason why we should work toward such an ideal, and the following suggestion is offered. To make it perfectly clear, some details must be given, but there is no insistence on these as essentials, though some of them probably would be. The sugges-

tion is to form a national body, representative in its membership, of all national engineering societies. All trade and business organizations to be excluded. The content of the suggestion can be most easily given by a skeleton constitution as follows:

Name. American Engineering Association.

Object. To assist in the realization of the ideals of the engineering profession and to extend the usefulness of the professional engineer as a servant of the community.

Membership. Any national society of professional engineers, with or without associated grades of membership, to be eligible. No personal membership. Member societies to elect representatives annually on a numerical basis, *e.g.*, one representative for 3000 members or less, and one representative for each additional 1000 members. Representatives to have terms of three years and to be ineligible for re-election. Terms to be arranged in rotation groups. Officers to be elected by representatives annually.

Support. To be by annual assessment of member societies on per capita basis.

Functions. To arrange an annual convention of engineers for discussion of engineering in general, of the engineering profession, and of any related subjects, except scientific and technical subjects such as would naturally and properly come before meetings of member societies.

To hold not less than two other meetings each year at which the objects of the association would be discussed and recommendations forwarded to the member societies, if desirable.

To investigate and report on, with recommendation, any subject which might be referred to it by a member society.

To appear at congressional, legislative or other hearings where it may be desirable, for the purpose of assisting in a proper decision of questions affecting the public good.

To make recommendations at any time to public officers as to policy in relation to matters in which the engineering profession may be interested on its own account or on account of its share in responsibility for public progress.

As the title states, this is merely a suggestion offered, in brief form, to provoke discussion. Everyone will probably agree that the subject is a most serious one and worthy of attention. Should the suggestion be received favorably it could be referred to the Board of Directors. No attempt should be made to carry any such scheme into effect until at least three of the four great national engineering societies could endorse the final plan.

DISCUSSION ON "A SUGGESTION FOR THE ENGINEERING PROFESSION" (MCCLELLAN), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

C. O. Mailloux: Mr. Chairman and gentlemen, I regard this paper as one of the most interesting papers that has been presented to the Institute for some time. The President has said that this is *the method* of raising the social status of engineers. I look upon it as *a* method, because I think there are many methods. I have looked forward for many years to greater coöperation among engineers. It has been one of my hobbies. There has been a tendency among engineers to segregation; the different bodies have tended to undergo a process of evolution in different directions, in many respects, in regard to their points of view, and their attitude towards public questions, and also even in regard to their ethics and their methods of professional discipline and conduct. Many engineers in the different branches of engineering realize this, and they also realize the importance of doing something to improve conditions; and various remedies to overcome the conditions that now exist have been proposed.

The American Institute of Consulting Engineers, which has recently come into some prominence, has attempted to bring together the different branches of the engineering profession into a body that will work for the profession of engineering in general. That body is interested more specifically in the welfare of consulting engineers, which is well enough, as far as it goes, but is, perhaps, not as good as it might be if it were sufficiently comprehensive to include engineers of all types, for there are many prominent and eminent engineers who are not consulting engineers, and can not be properly classed as such. I think the suggestion of Dr. McClellan is a very good one indeed. In the way he has formulated it, it is very excellent, but I am not so severe as he is inclined to be as to the means of carrying it out. I think the matter should be carried out by the Institute. It has been the pioneer of progress in the development of many good ideas in this branch of engineering, and in other branches of engineering, generally.

We have inaugurated the Section movement, which is being taken up by other branches of the engineering profession, and I do not see why this body should not be the fostering spirit of a movement of this kind, looking to coöperation among the different branches of the engineering profession.

I would like to make a motion that this matter be referred to the Board of Directors, as I consider it well worth the closest attention of the Board of Directors; and it should serve as the basis of a thorough study and investigation of the question, the Board of Directors to be given full power in the matter, and to indicate to the membership its conclusions in due course.

Oberlin Smith: As a long-time member of all four of the big engineering societies, I feel that perhaps I can speak on

this subject impartially, although I happen to be more closely related with the mechanical engineering branch than any other.

For many years past progressive engineers have hoped for a united engineering society of some kind. The movement was brought up some time ago, before the Engineering Societies Building in New York City was constructed, and the plan freely discussed, but with some of the societies there was too much of a clannish spirit to permit full and complete coöperation; hence nothing practical was done at that time. When, however, Mr. Carnegie gave us the building on 39th Street, many of us hoped that all four societies would come in. The fact that one of the societies remained out was a great disappointment, but I know that many members of the American Society of Civil Engineers much regret the separation. Last week at a convention of the Society in Ottawa,this feeling was brought out strongly and there was some manifestation of the spirit which has been shown in this splendid paper of Dr. McClellan's. The new president, Prof. Swain, of Harvard, gave us a most effective and interesting address. There were some things in it which seemed to be too conservative, yet he took a broad view of the subject, and regret was expressed that the various societies had not all gotten together before. At the meeting, however, there was in evidence some of the old idea that civil engineers were most important, because they covered all the ground outside of military engineering.

It seems to me that we all might get nearer together by mixing, so to speak, the councils of the different societies. Some members of the Mechanical Engineers who are also members of the Electrical Engineers should be in the Council of the Electricals, and vice versa; and this system of mixing of interests would certainly tend towards greater unity and efficiency.

Thus in the Council of each Society, there would be a few of the best-known and most fit members of each of the other societies.

There have, so far, been but few electrical, mechanical, or mining engineers represented on the Council of the American Society of Civil Engineers. I do not remember whether there are any now. Under such conditions a society can hardly claim to be at the head of all engineering activities.

I think, however, that the feeling is growing all the time, among the members of the various societies, that there should be a greater coming together, but they are not limited to the four old organizations above mentioned.

We have among them an important society, the Naval Architects and Marine Engineers; and we have numerous smaller societies, like the Society for Testing Materials, the Society for Engineering Education, the Illuminating Engineering Society, and similar organizations. We are one family subdivided into smaller branches. Of course, there are all kinds of specialties in engineering, just as there are in other professions. Spec-

ialization is increasing all the time, and must be expected. No one man can acquire thoroughly all engineering knowledge. If he knows his own specialty well, and knows about other things in only a general way, he will be likely to make a successful engineer.

I thoroughly agree with Dr. McClellan's idea that we should make some beginning and start in to organize a United Engineering Society. It would probably be impracticable to make the membership of individuals, but it could be made up of other organizations, as suggested. There is no reason why it should not be a unit by itself and have its complete individual organization, with its own separate meetings. Not only could such a society handle the matter of ethics, which has been so well taken care of by this society, but it could make suggestions for better laws and better government in all sorts of ways; and it would have a broad influence, scientific, economic, moral and social, which engineers do not now possess. We could exert our influence in a powerful way by united strength, rather than individually, as we now do. I look forward to such a movement being a wonderful success.

Chas. L. Clarke: Dr. McClellan seems to be in doubt as to whether the time is ripe for an organization of this sort. Undoubtedly the time is here, and we ought to see such an organization founded before long. The danger that it might interfere with the so-called clannishness of the member societies, is hardly possible, because the plan does not propose interference in any way with the technical business or other individual matters of such societies, but only contemplates fostering national and broad policies affecting the body politic in general, as far as engineers can help to do so, as men of education and of technical judgment.

Dr. McClellan has invited suggestions on two points. The speaker has one suggestion to make with reference to the name of the society. According to the suggestion in the paper of Dr. McClellan, it is to be called the American Engineering Association. The speaker proposes that it be called the American Association of National Engineering Societies, which title seems to explain as briefly as possible what the Association is in fact, and is calculated favorably to attract attention of Congressmen when receiving a communication relative to pending legislation sent to them by this proposed Association, for they will see just what it stands for and comprehend the situation from its name, especially if coupled with a list of its members.

D. B. Rushmore: We received a great deal of inspiration from the Address of the President this morning, and we have also been greatly impressed by the suggestions made by Dr. McClellan in his paper, and these things together lead me to believe that there is very great necessity now for some one to take these ideas and reduce them to general principles, so that the best results from coöperative effort may be secured therefrom. However, I am afraid that we are getting into a

condition of over-organization all over the country. If we take our political life, our industrial life, our social life, and our professional life, we will find that we belong to a great many more organizations than we can take an active part in.

Here we have a very interesting proposition brought forth, and the question arises: What is its practical value? Can we express in general terms this particular hope we wish to accomplish? To a person who has had to work in a large organization, and possibly not especially fitted to adapt himself to others, it has been necessary many times to think— Why an individual? Why a department? Why an organization? And what is it trying to do? All over the country you see rising up industrial organizations, political organizations, and agricultural organizations. In the agricultural organizations an interesting development is taking place. In these organizations a differentiation is being made between those things most efficiently done by individuals and those best accomplished by coöperative effort. They are being organized from beneath upward, the individual action extending as far as efficient results justify it, and further on coöperative effort is substituted, with the most beneficial results for all concerned.

In our field of engineering activities we have a large number of small societies, all actively engaged in fields of special effort. A similar result could be accomplished by joining all of these in one large holding company, and instead of separate entities, having them as members of one large whole. It is, however, a question, and a serious one, as to which method of organization will produce the better results.

It is absolutely essential for the future welfare of the engineer that he should not allow himself to be pushed into the field of an exclusively pure scientist, but that he demand that his work include the consideration of money expenditures, which factor is one of the basic principles of engineering practise.

The standing of the engineering organizations and their value to their membership will depend upon the part which these organizations play in the field of industrial, social and political activity. It is most important that an unrelenting fight be waged against the licensing of engineers by the State. We should insist that the membership rank of the engineering societies be accepted as the means by which the standing of an engineer in his own profession shall be judged. This means that considerable revision must be made of the grades of membership and the requirements for admission to such society.

Dr. McClellan's suggestion has much of value and is of interest to all engineering societies. It is worthy of much consideration, but it is suggested that it receive the benefit of all possible criticism before we organize another society.

C. L. deMuralt: I am very much pleased with Dr. McClellan's paper, and heartily endorse what Mr. Mailloux has hinted at, namely, that it is just about the right time to have this sug-

gestion made. Dr. McClellan has put it in very good form, even down to the details.

If I say anything at all, it is because I desire to make an additional suggestion: Why is it necessary to add to the many existing societies a new one? Why can we not use one which is already in existence?

The American Society of Civil Engineers is unfortunate in that its name, according to present usage, seems to cover one branch of the engineering profession only. That is not so. Many of us are members of the Americal Society of Civil Engineers, and the American Society of Civil Engineers has always taken the view that it is the old mother society which represents all engineers in this country. Why should we not approach the American Society of Civil Engineers through our Directors, perhaps in coöperation with the American Society of Mechanical Engineers, the Society of Naval Architects and Marine Engineers, the American Institute of Mining Engineers, and similar bodies, and discuss with them this proposition which Dr. McClellan has made.

I am not authorized to speak for the American Society of Civil Engineers, but many of the members of that Society have told me they would like to have the support of the individual engineering societies. I have no doubt they would listen to any reasonable suggestion of having the individual societies come in with them on some broad basis. This could either be done as Dr. McClellan's paper suggests, through a lump sum payment from each society or else by allowing the individual members, if they want to join the American Society of Civil Engineers, to obtain membership by paying some agreed-upon additional fee. I think that along these lines something of real practical value could be accomplished in the direction of Dr. McClellan's suggestion.

C. O. Mailloux: I want to say a word on this question of the role or function which the American Society of Civil Engineers might have played. The American Society of Civil Engineers had the opportunity to lead all the engineering societies of this country, but lost that opportunity thirty or forty years ago, and it is too late to go back to it. The suggestion which Mr. de Muralt made would meet with enormous opposition in the minds of a few fossilized civil engineers who believe in the lion and the lamb lying down together, provided the lamb is inside of the lion. When the lion has become a small thing, dwarfed, in comparison with the lamb, the suggestion is preposterous. I am second to none in my respect for ideals in engineering, and I think I have done my share in the work of raising the ideals of engineering. I know we cannot accomplish the objects which Dr. McClellan seeks to accomplish by proceeding along that line, for the reason that the very things he seeks to have done, namely, the pursuit of ideals, the participation of the engineering profession in the consideration and determination of public

questions, are notoriously the very things which the American Society of Civil Engineers has always dodged and kept away from, and on which it has been afraid to hold distinct and pronounced opinions.

C. L. de Muralt: That, of course, is an individual opinion. It may be shared by many here, but I do not quite see why my proposition is necessarily ridiculous and preposterous. The American Society of Civil Engineers might have had some fossilized members thirty or forty years ago—I was not an engineer at that time—but it does not seem to me fair to cast reflections upon the present membership of that Society on the basis of what happened thirty or forty years ago. I know, as a positive fact, that those who are now managing that Society are not fossilized and I have reason to believe that they are very much in favor of such a movement. They should be approached to find out if it is not possible to carry out Dr. McClellan's idea, without starting a new and unnecessary society.

Oberlin Smith: The American Society of Civil Engineers was, I think, the first engineering society of consequence established in this country. I have great respect for it as a body, but it constitutes only one branch of the profession. Applied to their branch only, the term "Civil Engineers" is a misnomer, and does not mean anything, because most of the rest of us are also "civil". The term was of course used in contradistinction to the term "military engineers," and was applied to all engineers other than those engaged in military work. Although not logical as at present used, it probably will remain with us, but it cannot be a comprehensive name for a united society. If we have a new society, we should not call it "The American League of National Engineering Societies." We rarely could spend the time to pronounce the whole name, but would call it by its initials. Witness the sad case of the American Society for the Prevention of Cruelty to Animals; we always call that the A. S. P. C. A. and then have to think it out. There is a great advantage in having a short name for a society or other organization so that people will be able quickly to remember what the initials stand for. We should have "American Engineering League," or some such name, the shortest that we can get. If a Congressman or such should not know what A. E. L. stood for, we could have the full name presented for his notice, far better than we could a very lengthy one.

D. C. Jackson: This paper has much of suggestiveness in it, and it proposes one of those things which ought to be put into execution. It is one of those things which has been discussed year after year for a long period of time. I hope that Dr. McClellan's entry into the lists will result in the accomplishment of the purpose. I am with him thoroughly, but I want to criticize his paper in a small way.

We generally recognize, I think, that the old definition that comes down from Tredgold, that "Engineering is the directing of

ne forces of nature [illegible]
orrect definition [illegible]
l modern engineering [illegible]
efinition of engineering, [illegible]
e definition of engineer [illegible]
ive, devise and organize [illegible]
the use and convenience of man [illegible]
en it is not quite [illegible]
s Dr. McClellan's [illegible]
e men who are [illegible]
engineering and doing [illegible]
e must include within [illegible]
sts primarily, and engineer [illegible]
ust also to some degree [illegible]
me men who are executive [illegible]
terprises, and also [illegible]
eir active work [illegible]
other words, [illegible]
e profession as [illegible]
l these men. This is [illegible]
lmirable paper, but [illegible]
osed classification should be modified.

paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

EST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND

BY A. E. KENNELLY AND F. W. LIEBERKNECHT

[t is the purpose of this paper to describe in detail a series of asurements of voltage and current made, in February, 1913, er an artificial telephone line 800 km. (nearly 500 miles) long. hough it is possible to compute the behavior of such a line en its electrical constants are known, yet this is the first time, far as the authors are aware, that an artificial aerial line has n measured both as to amplitude and phase of voltage and rent, with less than 2 volts of 750 cycles-per-second frequency pressed at the sending end.

he artificial line used in these measurements is the one manently installed in the Graduate School of Applied Science Harvard University, and described in our paper before the ston Convention of the A. I. E. E. last year, in relation to power-transmission.[1] In order to convert this artificial , originally designed as a power-transmission line, into an al telephone line, small non-inductive resistances were uninly inserted in the line, one to each section.[2] These resistes added 100 ohms per section of 80 km., or increased the inal linear resistance from about 0.3 ohm per wire-km.,

Measurements of Voltage and Current over a Long Artificial Powersmission Line at 25 and 60 Cycles per Second, by A. E. Kennelly and 7. Lieberknecht. TRANS. A. I. E. E., Vol. XXI, p. 1131.

These resistances were made of about 6 meters of No. 32 A. W. G. a (0.2 mm. 0.008 inch bare diam.) double-cotton covered resist- wire, and were wound non-inductively on fiber strips 8 cm. long, cm. wide, and 0.3 cm. thick, soldered to terminals on the same, and red in solid paraffin wax. These resistances carry 0.5 ampere with- serious heating.

(0.48 ohm per wire-mile), to about 1.55 ohms per wire-km. (2.5 ohms per wire-mile), corresponding approximately to one of a pair of copper overhead telephone wires of copper 3.75 mm. (148 mils) in diameter. That is, one and the same artificial line of coils and condensers can be made to serve either as an artificial aerial power-transmission line, or as an artificial aerial telephone line, by respectively cutting out or in the non-inductive resistance attached to each section, thereby changing the line for low frequencies from about No. 0 B. & S. gage (8.3 mm. 0.325 in. diameter) to No. 7 B. & S. gage (3.65 mm. 0.144 in. diameter).[3] The total available length of line in each case is 2400 km. (1491 miles), only 800 km. (497 miles) being employed in the tests here reported.

For the constructive details of the line reference may be made to our paper of last year already cited.[4] It may suffice to say at

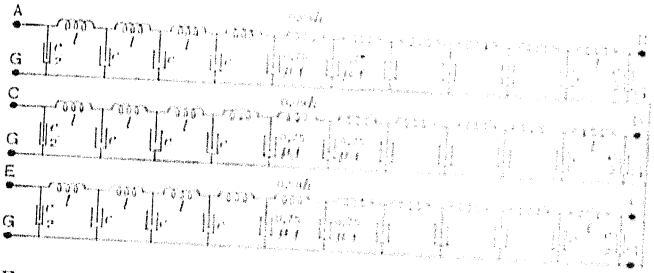


FIG. 1—DIAGRAM OF CONNECTIONS OF ARTIFICIAL LINE

this time that the line used was a Π-line of ten sections, with ground return, the connections being indicated in Fig. 1. The constants for the line appear in Tables I and II. In the design and construction of an artificial aerial telephone line *per se*, not intended to serve also as a power transmission artificial line, it would be unnecessary to use as much copper as in the artificial line here described. It would also be desirable to subdivide the inductance and capacity into smaller but more numerous sections for frequencies much above 1000 cycles per second. In the line

3. The line actually behaved, at telephonic frequency, like one of a pair of No. 9 A. W. G. copper wires (2.9 mm., 0.114 in., diam.), owing to the combined influences of capacity between the layers of the coil winding, and the lumpiness of the line section. See Table VI.

4. See also an article "Artificial Power-Transmission Line," by A. E. Kennelly and H. Tabossi, *Electrical World*, New York, Feb. 17, 1912, giving the constructive details of the artificial line.

here described, there were five sections per actual wave-length, at 760 cycles per second.

It will be observed that whereas the apparent inductance of the artificial line is the same at both telephonic and lighting frequencies, the apparent leakance is more than ten times greater at the telephonic frequency while the apparent resistance is nearly four times less, and the apparent capacitance 11.3 per cent less. In other words, the effect of increasing the testing frequency on the artificial line from 60 to 760 cycles per second, is to change all the constants except the inductance. Each coil

TABLE I

ELECTRICAL CONSTANTS OF TEN-SECTION ARTIFICIAL LINE AT 60 ~

	Resistance at 20° cent. ohms	Inductance henrys	Capacitance microfarads	Leakance micromhos	Hyp. angle hyps.
Whole line....	1256	0.913	7.5	120	1.08 /71°.5
Per section..	125.6	0.0913	0.75	1.2	0.108 /71°.5
Per wire-km.	1.57	1.14×10^{-3}	9.38×10^{-3}	0.15	0.00136 /71°.5
Per wire-mile	2.53	1.84×10^{-3}	15.1×10^{-3}	0.24	0.00219 /71°.5

TABLE II

ELECTRICAL CONSTANTS OF ARTIFICIAL LINE AT 760 ~

	Apparent resistance at 20° cent. ohms	Apparent inductance henrys	Apparent capacitance microfarads	Apparent leakance micromhos	Hyperbolic angle Hyps. /_	Surge impedance ohms /
Whole line..	330	0.9136	6.656	1660	12.94 /79°.5	465 \11°
Per section...	33	0.0914	0.6656	166	1.294 /79°.5	465 \11°
Per wire-km...	0.413	1.14×10^{-3}	8.32×10^{-3}	2.075		
Per wire-mile...	0.665	1.84×10^{-3}	13.4×10^{-3}	3.34		

behaves as though its resistance were 33 ohms instead of 125.6. Its condensers (paper dielectric) behave as though their capacitance had fallen 11.3 per cent while their leakance had risen some ten times. It is known that paper condensers are subject to such changes with rise of frequency.[5] The great apparent reduction in coil resistance can, however, only be attributed to to the effect of the lumpiness of the artificial line. This

5. "The Capacity and Phase Difference of Paraffined Paper Condensers as Functions of Temperature and Frequency," by Frederick W. Grover, *Bulletin of the Bureau of Standards*, Vol. VII, No. 4, February 28, 1911.

deduction was supported by tests made on the coils alone, at telephonic frequency.

Generator. The alternator used was a Cahill multifrequency generator employing a number of stator armatures side by side, with internal rotor field magnets on the same shaft, giving respectively 2, 4, 8, 16, 32 and 64 cycles per revolution. It was directly coupled through a leather-strip coupling to a 500-volt, four-kw., four-pole direct-current motor. Each of the component alternator armatures was rated at about 500 watts output. Only two of the armatures were used, namely, those giving 2 and 32 cycles per shaft revolution. When running at 1425 rev. per min. or 23.75 rev. per sec., these armatures delivered frequencies at 47.5 ∼ and 760∼ respectively. The former was used to supply a Frahm vibrator frequency indicator, and the latter for the test of the artificial line. When the frequency meter indication was steady at 47.5 ∼, the artificial-line frequency was known to be 760 ∼. By leading the shunt-field circuit of the

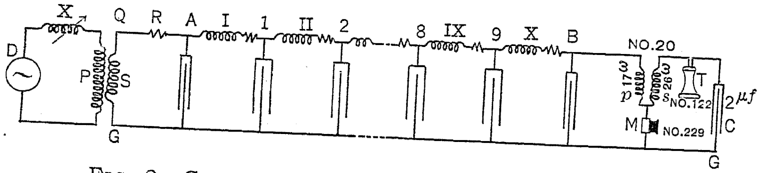


FIG. 2—CIRCUIT CONNECTIONS OF ARTIFICIAL LINE

driving motor into the artificial-line room, an adjustable field rheostat in this room enabled the driving-motor speed to be kept constant, and thus also the alternator frequencies.

Frequency. The reason for selecting 760 cycles per second for testing the artificial telephone line was that this is near to the standard telephone frequency of 5000 radians per second (795.8 ∼) which has been accepted internationally. It is also known to be near to the fundamental frequency of the diaphragms of the standard receiving telephone used.[6]

Circuit Connections. The circuit connections of the artificial line are indicated in Fig. 2. The alternator stator armature *D* delivered 40 volts at 760 ∼ in the testing room. A step-down

6. "The Impedance of Telephone Receivers as Affected by the Motion of Their Diaphragms," by A. E. Kennelly and G. W. Pierce, *Proc. Am. Ac. of Arts and Sci.*, Vol. XLVIII, No. 6, September, 1912, p. 113; also *Electrical World*, New York, September 14, 1912; and "The Humming Telephone," by A. E. Kennelly and W. L. Upson, *Proc. Am. Phil. Soc.*, 1908.

transformer, $P\ S$, lowered the voltage to about 1.75 volts at secondary terminals $G\ Q$. The adjustment was made by inserting an adjustable reactance X in the primary circuit, partly for the purpose of reducing upper harmonics in the wave of secondary voltage. The voltage wave-form was somewhat peaked. That is, a symmetrical third harmonic was perceptible; but no analysis of the wave form was attempted. The secondary terminal Q was connected to the end A of the artificial line through a non-inductive resistance R of 100 ohms. The other secondary terminal G was connected to the ground return of the artificial line, and was also carefully grounded.

Three series of tests were made, namely, with the distant end of the line (1) freed, or open, (2) grounded, and (3) connected to ground through a standard subscriber's set.

The third condition is indicated in Fig. 2.

Telephone circuits actually employ metallic return, and not ground return; but all tests on ground-return artificial lines are immediately interpretable on metallic-return or loop basis. These tests correspond to applying 3.5 volts at the sending end of a loop, and two subscriber's sets in series at the receiving end.

Method of Measurement and Apparatus Used

The potential and current along the line in the steady state were measured by means of a Drysdale a-c. potentiometer, using a Duddell vibration galvanometer. The Drysdale instrument was described with some detail in our A. I. E. E. paper of last year, above-mentioned. Since the potential on the line nowhere exceeded 1.8 volts, the potentiometer was able to read the potential at any junction point directly, without the intervention of a multiplier or step-down transformer. In order to find the current strength, the drop of potential in the 100-ohm inserted section-resistances was measured.

The Duddell vibration galvanometer[7] was tuned to the testing frequency and operated with the aid of an arc lamp. The spot of light was thrown on a white wall several meters away, so that it was easy to see when balance was secured and the spot of light brought to rest, from almost any part of the testing room.

The 760-cycle-per-second voltage was raised to nearly 140 volts by a step-up transformer, and impressed on the split-

7. "A Bifilar Vibration Galvanometer," by W. Duddell, *Proc. Physical Society*, London, May 14, 1909 and *The Electrician*, London, Vol. LXIII, pp. 620–622, July 30, 1909.

phase angle measurer of the instrument. The phase balance required about 0.043 microfarad and 340 ohms, inserted in the associated shunt circuit of the split-phaser. This split-phase balance had to be checked and adjusted occasionally.

Method of Observation

In making a series of tests along the line, the impressed e.m.f. and frequency at A, Fig. 2, were kept as nearly constant as possible. One observer watched the Frahm frequency meter, another changed the potentiometer leads along the line and watched the vibration-galvanometer arc-lamp. A third adjusted the potentiometer balance for amplitude and phase. Each voltage could ordinarily be measured to 0.001 volt, or closer, in amplitude and to a tenth of a degree in phase. This voltage represented either a potential from some junction point on the line to ground, or the potential drop in a section of 100-ohm resistance. In working out the results, they were all reduced by simple proportion to what would have been observed if the impressed e.m.f. at A had been just $1.00 \underline{/0^\circ}$ volt instead of the 1.7 volts, or thereabouts, actually measured. This reduction was made for greater simplicity in presenting the results.

Results

The results obtained are indicated in Tables III, IV and V for the condition, at the B end, of grounded, open, and through subscriber's set, respectively. Referring to Table III, the first column denotes the test-points along the line. Arabic numerals designate junction-points between sections, and Roman numerals mid-section points (see Fig. 2). The distances in kilometers of these points from the distant end of the line appear in column 2. The hyperbolic angle δ, of each point from B, is given in the next column, expressed as a complex quantity,[8] the real component being a hyperbolic angle, expressible in hyperbolic radians, and the imaginary, or j-component, a circular angle expressed in circular radians. This j-component measures the wave phase-length of the line at the frequency considered. In this case, the wave-length of the whole line AB is shown to be 12.723 circular radians. It is convenient for many purposes, however, to divide the j-component by $\pi/2$, or 1.5708, in order

8. "The Application of Hyperbolic Functions to Electrical Engineering Problems," by A. E. Kennelly, University of London Press, 1912, Chap. V.

to reduce this circular angle to quadrant measure. This reduction appears in the fourth column. The whole line AB subtends a complex hyperbolic angle $2.350 + j\,12.723 = 12.94\,\underline{/79.5}$ hyps., of which the j-component is 8.1 in quadrant measure. That is, the wave phase-length of the line is 8.1 quadrants, or a little more than 2 complete revolutions. In other words, the artificial line at this frequency covers a little over 2 complete wave-lengths, and the equivalent smooth line corresponding to the artificial line at junctions, would also cover a little over 2 complete wave-lengths. This hypothetical equivalent smooth line which would conform electrically to the lumpy artificial line at junction points, may be briefly denoted as the *imitated line.*

The fifth column of Table III gives the hyperbolic sine of the angle δ at the respective artificial-line junction points.[9] The potential along the artificial line from junction to junction, and on the imitated line at all points, follows sinh δ in simple proportion. The voltage E' so computed, appears in column 6, starting with $1.00\,\underline{/0^\circ}$ volt at $\sinh \delta = 5.2\,\underline{/9^\circ.2}$, phase angles appearing as degrees and decimals of a degree. Column 7 gives the corresponding observed junction-potential in magnitude and phase with the aid of the potentiometer, taking the initial impressed voltage as $1.00\,\underline{/0^\circ}$ volt. It will be noticed that the agreement between the computed voltage E' and the observed voltage E is satisfactory, the magnitudes usually agree within 5 per cent and the phase within 5 deg. A discrepancy of 5 deg. may seem considerable in itself, but the total change of voltage phase along the line is about 720 deg.

Column 8 gives the hyperbolic cosines of the mid-section angles. It has been shown[10] that the current in any Π-section of an artificial line, when multiplied by the hyp. cosine of a semi-section, agrees with the current on the imitated line at the corresponding point; also that the current at any point of a smooth line is directly proportional to the hyp. cosine of the angle from the distant end. Column 9 gives in this way the computed current at the points on the imitated line corresponding to mid-

9. Tables of complex hyperbolic functions expressed as sinh, cosh, or tanh of $(x + jq)$ from $x = 0$ to $x = 10$, and $q = 0$ to $q = \infty$, by steps in each of 0.05, have been computed, and are in course of publication by the Harvard University Press, together with large-scale interpolation charts.

10. "The Distribution of Voltage and Current over Artificial Lines in the Steady State," by A. E. Kennelly, *Electrical World*, New York, August 10, 1912.

TABLE III

LINE GROUNDED AT B

Point	Distance from B km.	Hyperbolic angle from B: $\delta = x + jy$ hyps. radians	quadrants	sinh δ	Voltage along line: E' computed volts	E observed volts	cosh δ	Current strength along line: I' computed	I observed milliamperes	I cosh u reduced
A	800	2.350 + j12.723	j8.10	5.20 /9°.2	1.000/0°	1.000/0°	5.288/8°.8	2.227/12°	2.227/12°	2.227 /12°
I	760	2.233 + j12.087	j7.695				4.710\27°.1	1.984\23°.9	2.454\32°	1.995 \27°
1	720	2.115 + j11.451	j7.290	4.165\64°.2	0.801\73°.4	0.797\84°				
II	680	1.998 + j10.815	j6.805				3.632\108°.1	1.531\104°.9	1.953\114°.2	1.588\109°.2
2	640	1.880 + j10.179	j6.480	3.275\134°.6	0.630\143°.8	0.625\152°.3				
III	600	1.763 + j 9.543	j6.075				2.964\173°.6	1.247\170°.4	1.538\180°	1.250\175°
3	560	1.645 + j 8.906	j5.670	2.545\212°.3	0.490\221°.5	0.482\228.2				
IV	520	1.528 + j 8.270	j5.265				2.181\244°	0.919\240°.8	1.150\255°.7	0.935\250°.7
4	480	1.410 + j 7.634	j4.860	2.158\281°.8	0.415\290°.7	0.427\302°				
V	440	1.293 + j 6.998	j4.455				1.847\323°.5	0.778\320°.3	0.923\332°.2	0.750\327°.2
5	400	1.175 + j 6.362	j4.050	1.466/5°.4	0.282\3°.8	0.286\5°				
VI	360	1.058 + j 5.726	j3.645				1.525\25°.9	0.642\22°.7	0.780\34°	0.634\29°
6	320	0.940 + j 5.089	j3.240	1.428\73°.5	0.275\82°.7	0.271\92°.3				
VII	280	0.823 + j 4.453	j2.835				0.955\111°.4	0.402\108°.2	0.510\121°.2	0.415\116°.2
7	240	0.705 + j 3.817	j2.430	0.994\126°.5	0.191\135°.7	0.199\143°				
VIII	200	0.588 + j 3.181	j2.025				1.177\178°.7	0.496\175°.5	0.618\185°	0.502\180°
8	160	0.470 + j 2.545	j1.620	0.749\237°.9	0.144\247°.1	0.140\253°.7				
IX	120	0.353 + j 1.909	j1.215				0.484\224°.8	0.204\221°.6	0.279\226°	0.227\221°
9	80	0.235 + j 1.272	j0.810	0.982\274°.2	0.1889\283°.4	0.1965\294°				
X	40	0.118 + j 0.636	j0.405				0.813 \355°	0.342\351°.8	0.439\0°	0.356\355°
B	0	0. + j 0	j0	0.	0.	0.	1.000/0°	0.421\356°.8	0.439\0°	0.439\360°

section points on the artificial line. Column 10 gives the observed section current I, and the last column gives $I \cosh u$, $\cosh u$ being, for this line, the vector $0.813 \angle 5°$. The agreement should be exact, theoretically speaking, between the entries in columns 9 and 11 under I' and $I \cosh u$ respectively. It is not exact in the case considered, but is nevertheless satisfactory.

Table IV gives the corresponding computed and observed potentials and currents with the distant end free. Here the free end of the line constitutes an initial line angle of $j\,\pi/2$ or $j\,1.5708$ radians at B, or just 1 quadrant, which has been added

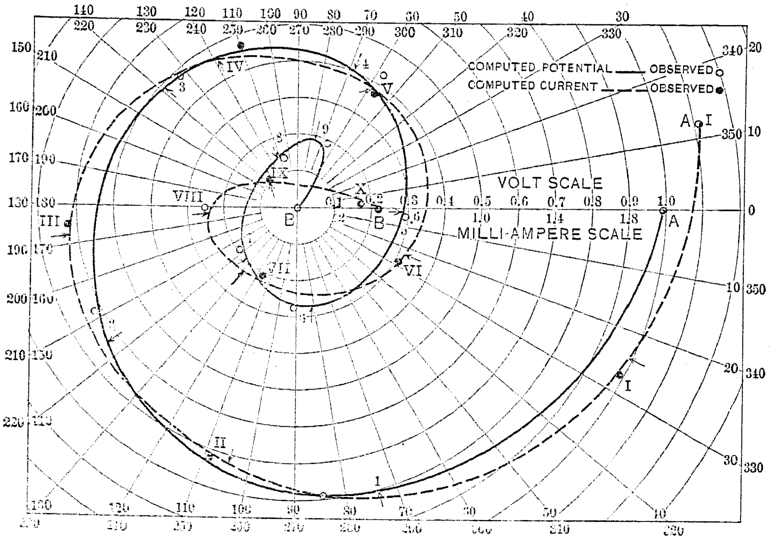


FIG. 3—LINE GROUNDED AT DISTANT END. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

to all the angles. The voltages follow the sines, and the currents the cosines, of the angles from point to point. The agreement is again satisfactory, although by no means exact, between E' and E, also between I' and $I \cosh u$.

Table V gives a similar comparison of computed and observed potentials and currents for the case of the line grounded at the distant end through a subscriber's set which offered an impedance of $1570 \angle 70°$ ohms, and which therefore subtended a terminal angle of $\tanh^{-1}\left(\dfrac{1570 \angle 70°}{465 \angle -11°}\right) = 0.043 + j\,1.285$ hyp.; or, with

TABLE IV

LINE FREED AT B

Point	Distance from B km.	Hyperbolic angle from B: $\delta = x + jy$ hyps. radians	Hyperbolic angle from B: quadrants	$-j \sinh \delta$	Voltage along line: E' computed volts	Voltage along line: E observed volts	$-j \cosh \delta$	Current strength along line: I' computed	Current strength along line: I observed milliamperes	Current strength along line: $I \cosh u$ reduced
A	800	2.350 + j14.294	j9.10	5.288/8°.8	1.000/0°	1.000 /0°	5.20/9°.2	2.100 /13°	2.100/13°	2.100/13°
I	760	2.233 + j13.658	j8.695	4.109\64°.2	0.777\73°.0	0.7605\78°	4.717\26°.7	1.905\22°.9	2.286\31°	1.858\26°
1	720	2.115 + j13.022	j8.290							
II	680	1.998 + j12.386	j7.805	3.283\137°.5	0.6209\146°.3	0.6060\151°.8	3.743\107°.2	1.512\103°.4	1.917\109°.9	1.559\104°.9
2	640	1.880 + j11.750	j7.480							
III	600	1.763 + j11.114	j7.075	2.609\208°.9	0.4934\217°.7	0.4857\219°.1	2.753\176°.6	1.112\172°.8	1.385\176°.2	1.126\171°.2
3	560	1.645 + j10.477	j6.670							
IV	520	1.528 + j 9.841	j6.265	1.950\285°.7	0.3688\294°.5	0.3671\300°.1	2.380\248°.5	0.9613\244°.7	1.183\255°.8	0.962\250°.8
4	480	1.410 + j 9.205	j5.860							
V	440	1.293 + j 8.569	j5.455	1.773\356°.3	0.3353\5°.1	0.3358\3°.2	1.806\312°.2	0.7294\308°.4	0.8943\320°.0	0.727\315°
5	400	1.175 + j 7.933	j5.050							
VI	360	1.058 + j 7.297	j4.645	1.129\63°.0	0.2135\71°.8	0.2175\72°.9	1.370\38°.0	0.5533\34°.2	0.6874 \40°.2	0.559\35°.2
6	320	0.940 + j 6.660	j4.240							
VII	280	0.823 + j 6.024	j3.835	1.088\153°.4	0.2058\162°.2	0.2052\164°.1	1.247\113°.2	0.5036\109°.4	0.6942\108°	0.564\103°
7	240	0.705 + j 5.388	j3.430							
VIII	200	0.588 + j 4.752	j3.025	0.9547\196°.0	0.1805\204°.8	0.177\203°.9	0.624\172°.8	0.2520\169°.0	0.3172\177°.1	0.258\172°.1
8	160	0.470 + j 4.116	j2.620							
IX	120	0.353 + j 3.480	j2.215	0.3854 \322°.8	0.0729 \331°.6	0.0726\331°	1.012\263°.5	0.4088\259°.7	0.528\269°.5	0.429\264°.5
9	80	0.235 + j 2.843	j1.810							
X	40	0.118 + j 2.207	j1.405				0.603\279°.1	0.2435\275°.3	0.303\282°.2	0.246\277°.2
B	0	0. + j 1.571	j1.000	1.000 \0°	0.1891\8°.8	0.191\6°.7	0.	0.	0.	0.

the j-component in quadrant measure, $0.043 + j0.818$, the surge-impedance of the artificial line being $465 \backslash 11°$ ohms. All the angles of Table III are here increased by these amounts. The potentials are then simply proportional to sinh δ, and the currents to cosh δ, as before. A satisfactory agreement is found between the columns under E' and E; and also under I' and I cosh u.

Figs. 3, 4 and 5 are vector charts, corresponding respectively to Tables III, IV and V. Referring to Fig. 3, with Table III, it will be seen that the potential at A commences at $1.0 \underline{/0°}$ volt. The continuous curve then traces the hyperbolic-sine locus of

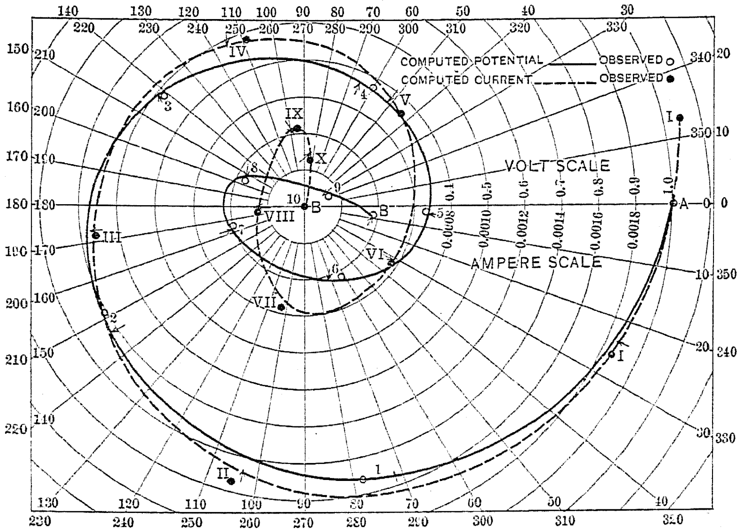


FIG. 4—LINE FREED AT DISTANT END. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

potential along the imitated line, both in magnitude and phase, it being understood that equal distances in kilometers do not generally correspond to equal phase differences. The arrowheads, intersecting the potential curve, mark the points on the imitated line at 80-km. intervals, corresponding to the junctions of the artificial-line sections. A small circle marks the corresponding vector potential observed. The arrowheads and circles should coincide, theoretically. Similarly, the broken line traces the computed hyperbolic-cosine locus of the vector-current along the imitated line, arrowheads indicating points at 80-km. intervals corresponding to mid-sections on the artificial line.

TABLE V

LINE GROUNDED AT *B* THROUGH SUBSCRIBER'S SET

Point	Distance from *B* km.	Hyperbolic angle from *B*: $\delta = x + jy$ hyps. radians	quadrants	sinh δ	Voltage along line: *E'* computed volts	*E* observed volts	cosh δ	Current strength along line: *I'* computed	*I* observed milliamperes	*I* cosh *a* reduced
A	800	2.393 + j14.008	j8.918	5.520 82°.2	1.000 0°	1.000 0°	5.477 81°	2.000 12°	2.000 12°	2.000 12°
I	760	2.276 + j13.372	j8.513							
1	720	2.158 + j12.736	j8.108							
II	680	2.041 + j12.100	j7.703	4.272 [illegible]°.7	0.774 72°.5	0.762 78°.6	4.976 44°.5	1.907 24°.5	2.362 51°	1.920 2[illegible]°
2	640	1.923 + j11.464	j7.298							
III	600	1.806 + j10.828	j6.893	3.463 64°.1	0.6274 11[illegible]°.3	0.616 151°.6	[illegible] 26[illegible]°.5	1.471 95°.3	1.935 105°.8	1.573 105°.8
3	560	1.688 + j10.191	j6.488							
IV	520	1.571 + j9.555	j6.083	2.704 153°.8	0.4899 216°.0	0.488 219°.1	[illegible]	1.106 168°.9	1.427 176°.7	1.1[illegible] 1[illegible]°.7
4	480	1.453 + j8.919	j5.678							
V	440	1.336 + j8.283	j5.273	2.077 211°	0.382 293°.4	0.379 301°.8	[illegible] 171°.7	0.9462 240°.7	1.218 254°.6	0.9[illegible]
5	400	1.218 + j7.647	j4.868							
VI	360	1.101 + j7.011	j4.463	1.828 [illegible]	0.3008 [illegible]	[illegible]	1.8[illegible]7 [illegible]	0.704 [illegible]	0.851 [illegible]	0.692 [illegible]
6	320	0.983 + j6.374	j4.058							
VII	280	0.866 + j5.738	j3.653	1.152 335°.5	0.2087 73°.7	0.2071 78°.2	1.5[illegible]	0.5879 [illegible]	0.7386 [illegible]	0.601 [illegible]
7	240	0.748 + j5.102	j3.248							
VIII	200	0.631 + j4.466	j2.843	1.23[illegible] 73°.1	0.2239 137°.3	0.2255 13[illegible]	1.2[illegible] 27[illegible]	0.4078 [illegible]	0.6[illegible]02 [illegible]	0.537 [illegible]
8	160	0.513 + j3.830	j2.438							
IX	120	0.396 + j3.194	j2.033	0.8[illegible] 110°.4	0.1511 [illegible]	0.1[illegible]	0.72[illegible] 117°.8	0.2772 [illegible]	0.5381 [illegible]	0.28[illegible]
9	80	0.278 + j2.557	j1.628							
X	40	0.161 + j1.921	j1.223	[illegible]	0.1143 325°.0	0.111[illegible]	1.[illegible]78 178°.7	0.2131 24[illegible]°.7	[illegible]	0.4[illegible]
	0	0.043 + j1.285	j0.818	[illegible]	0.177[illegible]	0.1[illegible]	[illegible]	0.1514 [illegible]	0.1[illegible]	0.1[illegible]
							[illegible]	0.1121 82°	0.11[illegible]	0.11[illegible]

The black dot circles mark the reduced current measurements. These arrowheads and black dots should also coincide, according to theory.

It will be seen that the current leads the impressed e.m.f. at *A* by 12 deg. As we advance down the line, both potential and current fall behind the phase of the impressed terminal e.m.f. The change in phase is about 720 degrees for potential, and 732 degrees for current; or about 0.9 deg. per km.

In the case of Fig. 4 and Table IV, it will be noted that freeing the line at the distant end, slightly diminishes the current at

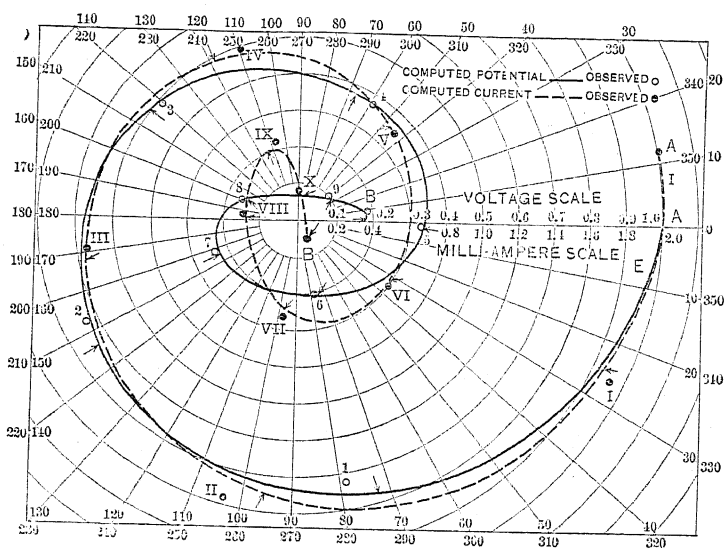


FIG. 5—LINE GROUNDED THROUGH SUBSCRIBER'S SET. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

the sending end, without materially affecting its phase. Towards the distant end of the line, the magnitude and phase of the current are, of course, increasingly affected.

Figs. 6, 7 and 8 show the computed magnitudes of voltage and current along the imitated line without respect to phase. The broken dotted straight lines indicate the correspondingly computed magnitudes of voltage along the artificial line, on the assumption that the resistance and inductance are uniformly distributed in each section coil; also that the capacitance between the coil windings can be ignored. The voltages at

TABLE VI

ELECTRICAL CONSTANTS OF IMITATED LINE CORRESPONDING TO THE TEN-SECTION ARTIFICIAL LINE AT 760 ~.

	Resistance at 20° cent. ohms	Inductance henrys	Capacitance microfarads	Leakance micromhos	Hyperbolic Angle θ hyps. $\angle$	Surge Impedance z_0 ohms $\angle$	Remarks
Line (800 km.)...	2205	1.173	5.823	0	$12.94 \angle 79^\circ.5$ $= 2.35 + j12.72$ $= 2.35 + j\,\underline{8.10}$	$465 \angle \overline{11^\circ}$	The imitated line corresponds approximately to one of a pair of No. 9 A. W. G. copper wires, diameter 2.9 mm. 0.114 in. separated in air to a distance of 1000 diameters or 2.9 meters.
Per wire-km.....	2.756	1.463×10^{-3}	7.28×10^{-3}	0	$0.01618 \angle 79^\circ.5$ $= 0.00294 + j0.0159$ $= 0.00294 + j\,\underline{0.0101}$	$465 \angle \overline{11^\circ}$	
Per loop-km.....	5.512	2.926×10^{-3}	3.64×10^{-3}	0		$930 \angle \overline{11^\circ}$	Underscored imaginary quantities are in quadrant measure.
Per wire-mile....	4.44	2.35×10^{-3}	11.72×10^{-3}	0	$0.02604 \angle 79^\circ.5$ $= 0.00473 + j0.0256$ $= 0.00473 + j\,\underline{0.0163}$	$465 \angle \overline{11^\circ}$	
Per loop-mile....	8.88	4.70×10^{-3}	5.86×10^{-3}	0		$930 \angle \overline{11^\circ}$	

section-junctions and line-terminals then agree with those of the imitated line at such points. The current strengths in the artificial line would, if shown on the diagram, be constant in each section, and would be represented by horizontal straight lines, broken by vertical descents at leak-junctions. When multiplied by cosh u, these currents would agree with the imitated line currents at mid-section points.

In the case of Fig. 6 and Table VI, the current strength arriving at the subscriber's set is $0.115\,\overline{\backslash 62^\circ}$ milliampere. The potential difference at the terminals of the receiving telephone T was $0.040\,\overline{\backslash 230^\circ}$ volt, and taking the impedance of this

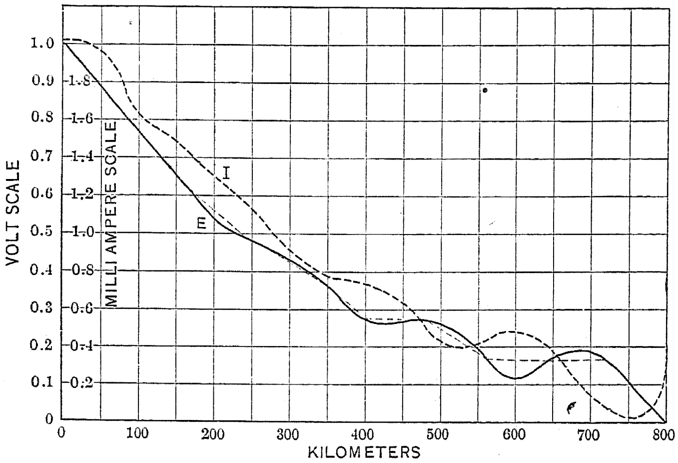


FIG. 6—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, GROUNDED AT DISTANT END

instrument at $260\,\underline{/40^\circ}$ ohms, as found by subsequent experiments, the current received in the instrument would be $0.040\,\overline{\backslash 230^\circ}/260\,\underline{/40^\circ} = 0.154\,\overline{\backslash 270^\circ}$ milliampere. This current gave rise to a loud musical note in the receiver.

EQUIVALENT CIRCUITS OF ARTIFICIAL AND IMITATED LINES

Table VII contains data concerning the artificial line taken as a whole, and also concerning the imitated line, its external counterpart. Figs. 9 and 10 show the nominal and equivalent circuits of these lines. In Fig. 9, the nominal Π, $A''B''$, contains an architrave impedance $2202 + j5599$ ohms, and the imitated

line would contain this impedance at the testing frequency. In each of the two terminal leaks there would be 0.01391 $/\underline{90°.5}$ mho, corresponding to 2.913 microfarads of total distributed capacity. Similarly, the nominal T, $A'B'$, contains in its arms a total of $2202 + j5599$ ohms, and in its single leak 0.02782 $/\underline{90°.5}$ mho.

Fig. 10 shows the equivalent Π, $A''B''$, of three simple impedances which would externally replace either the whole artificial line, or the imitated line. The architrave impedance is $2417 - j\,76$ ohms. Each pillar leak has an admittance of $(1.737 + j\,0.391)\,10^{-3}$ mho. If we apply one volt to the terminal A'', then by

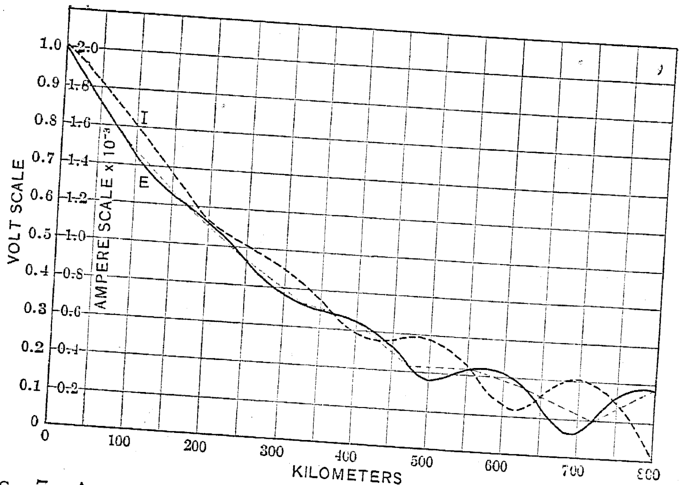


FIG. 7—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, FREED AT DISTANT END

freeing, grounding, or connecting-to-instrument the end B'', we obtain there the corresponding terminal voltages and currents observed and computed for the artificial line. That is, the current, voltage, and power will be the same at the terminals A'',B'', as at the terminals A and B respectively of the artificial line, or of the imitated smooth line, under like conditions of operation. Similarly, the equivalent T in Fig. 10, has $380 - j62.2$ ohms in each arm, and 11.19×10^{-3} $/\underline{20°.2}$ mho in its leak.

Free and Ground Impedance Tests of Artificial Line. Table VIII collects a set of measurements on the impedance of different lengths; *i.e.*, different numbers of sections in the artificial

line, commencing with one section and ending with 10 sections. Each impedance is the ratio of the terminal impressed voltage to the entering current strength. It will be seen that although the impedances, free and grounded at the far end, vary greatly as the number of sections is changed, yet their product is constant within errors of observation, and its square root, their geometric mean, is the constant surge-impedance of the line. The square root of the ratio of the two impedances also measures the tangent of the hyperbolic angle subtended by the line.

Precision of Measurements. Owing to the great sensitiveness of vibration galvanometers, it is readily possible to measure,

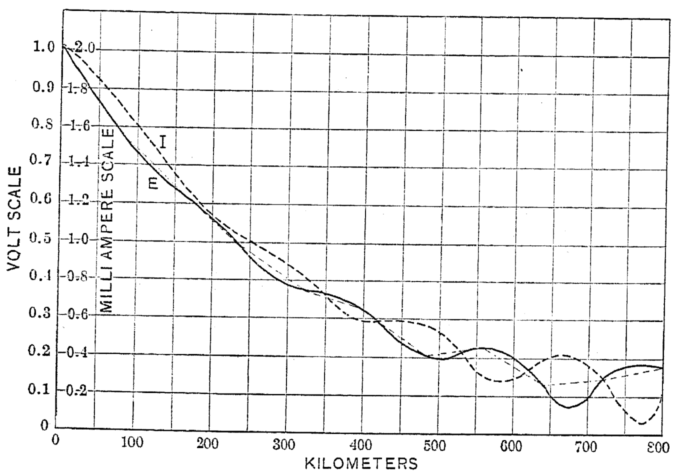


FIG. 8—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE, AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, GROUNDED THROUGH SUBSCRIBER'S SET AT DISTANT END.

as above described, the potential and current along an artificial line, fairly representing 800 km. (500 miles) of aerial telephone line, without using more than 1.75 volts at the sending end per wire, or 3.5 volts per loop on the metallic circuit basis. The precision of the measurements, however, is not so great at the telephonic frequency of 760 $\sim$, as at the lighting frequency of 60 $\sim$. This relative falling off in precision may be attributed to several causes: namely, first, capacity effects in apparatus and leads not noticeable at low frequencies; second, want of practise with the technique of the method and apparatus at the higher frequency; third, stray magnetic fields in coils and galvan-

TABLE VII

ELECTRICAL CONSTANTS FOR BOTH THE ARTIFICIAL AND IMITATED LINES

Angle θ hyps. $\angle$	Surge impedance z_0 ohms $\angle$	sinh θ	tanh $\theta/2$	Semi-section angle u	Correcting factors		
					cosh u	$\frac{\sinh\theta}{\theta}$	$\frac{\tanh(\theta/2)}{\theta/2}$
$12.94 \underline{/79^\circ.5}$ $= 2.35 + j12.72$ $= 2.35 + j\,8.10$	$465 \overline{\backslash 11^\circ}$	$5.2 \underline{/9^\circ.2}$	$0.8277 \underline{/1^\circ.7}$	$0.647 \underline{/79^\circ.5}$ $0.1175 + j0.636$ $0.1175 + j0.405$	$0.813 \underline{/5^\circ}$	$0.4018 \overline{\backslash 70^\circ.3}$	$0.1279 \overline{\backslash 77^\circ.8}$

Equivalent Π

Architrave impedance $\quad z_0 \sinh\theta = 2418 \overline{\backslash 1.8^\circ}$ ohms.

$= 2417 - j76$ ohms.

Pillar leak admittance $\quad 1/\{z_0 \tanh(\theta/2)\} = 1.78 \times 10^{-3} \underline{/12^\circ.7}$

Equivalent T

Arm impedance $\quad z_0 \tanh(\theta/2) = 385 \overline{\backslash 9.3^\circ}$ ohms.

$= 380 - j62.2$ ohms.

Staff leak admittance $\quad 1/(z_0 \sinh\theta) = 11.19 \times 10^{-3} \underline{/20^\circ.2}$ mho.

$= (10.5 + j3.862)\, 10^{-3}$ mho.

ometer leads, a very small flux alternating at the higher frequency, and linked with the galvanometer circuit, being able to set up a very appreciable e.m.f.; fourth, irregularities in the section condensers at the higher frequency (if the condensers along the artificial line are adjusted to equality at a low frequency they may readily show differences as well as diminutions in capacity at the higher frequency); fifth, deviation of the wave form of impressed e.m.f. from the sinusoidal, or the presence of harmonics. This affects the split-phase balance, and phase measurements. The vibration galvanometer may be broadly

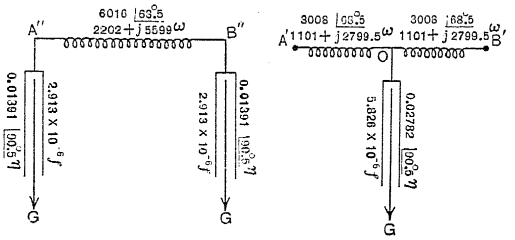


FIG. 9—NOMINAL Π AND T OF THE IMITATED LINE

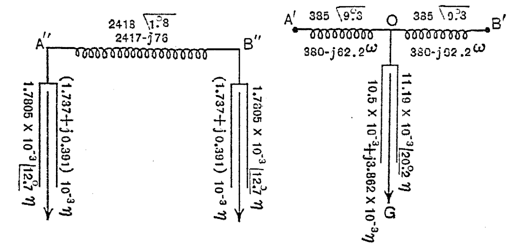


FIG. 10—EQUIVALENT Π AND T OF ARTIFICIAL AND IMITATED LINES

considered as responding only to the fundamental frequency, the harmonics being independent of it, and unable to affect it. Nevertheless, the presence of the harmonics is able to produce some disturbance of the zero, and thus may have some small influence on the measurements.

By practise, and with further experience, some of the above-mentioned disturbing sources may be reduced, and the precision of measurement increased. Nevertheless, the precision attained in the results here reported will doubtless be considered as satisfactorily sustaining the theory of such telephone-line transmission, at a single telephonic frequency, in the steady

TABLE VIII

IMPEDANCE TESTS OF ARTIFICIAL LINES OF DIFFERENT NUMBERS OF SECTIONS AT 760 ~

No. of sections	Impedance: Grounded Z_g ohms ∠	Impedance: Freed Z_f ohms ∠	$Z_g Z_f$ ohm² ∠	Surge impedance $Z_o = \sqrt{Z_g Z_f}$ ohms ∠	$\tanh \theta = \sqrt{Z_g / Z_f}$	θ	$2u$ mean section angle
1	1244/38°.4	167\56°	208300\17.6	456.4\8°.8	2.725 /47°.2	0.246 + j1.342	0.246 + j1.342
2	346.4\47°.3	623.8/28°.2	216100\19°.1	464.9\9°.55	0.7452\37°.75	0.497 + j2.583	0.249 + j1.292
3	441.3/14°.1	497.8\36°.3	219700\22°.2	468.7\11°.1	0.9415/25°.2	0.747 + j3.855	0.249 + j1.285
4	588\2°.6	337.5\16°.6	198470\19°.2	445.5\9°.6	1.320 /7°.0	0.940 + j4.510	0.235 + j1.128
5	387.7\10°.6	576.1\13°.5	223400\24°.1	472.7\12°.05	0.8203/1°.45	1.157 + j6.346	0.231 + j1.269
10	449.0\12°.0	476.2\13°	213800\25°	462.4\12°.5	0.9712/0°.5	2.35 + j12.72	0.235 + j1.272
Accepted mean values				465.\11°			0.235 + j1.272

state. A great variety of telephonic tests and measurements can be made on such an artificial line under different terminal conditions, and with different receiving instruments. Such an artificial telephone line has great practical value for the telephone engineer, the investigator and the student.

BIBLIOGRAPHY

GIVING AN INCOMPLETE LIST OF PAPERS REFERRING TO MEASUREMENTS ON ARTIFICIAL TELEPHONE LINES AND ALLIED TOPICS

A. E. Kennelly—" A Contribution to the Theory of Telephony," *Electrical World*, New York, Vol. XXIII, No. 7, p. 208, Feb., 1894, and *The Electrician*, London, June 29, 1894, Vol. XXXIII, p. 232.

M. I. Pupin—*Propagation of Long Electrical Waves*, TRANS. A. I. E. E., Vol. XVI, pp. 93–142, March 22, 1899.

M. I. Pupin—*Wave Propagation over Non-Uniform Cables and Long-Distance Air Lines*, TRANS. A. I. E. E., Vol. XVII, p. 385, May 18, 1900.

M. I. Pupin—" Wave Propagation over Non-Uniform Conductors," *Trans. Am. Math. Soc.*, Vol. I, No. 3, pp. 259–286, July, 1900.

G. A. Campbell—" On Loaded Lines in Telephonic Transmissions," Phil. Mag. Series VI, Vol. V, p. 313, March, 1903.

H. V. Hayes—" Loaded Telephone Lines in Practice," *Proc. Int. Elec. Congress*, St. Louis, Sec. G., Vol. III, p. 638, 1904.

J. A. Fleming—" A Model Illustrating the Propagation of a Periodic Current in a Telephone Cable and the Simple Theory of its Operation," *Phil. Mag.*, Aug., 1904, and *Proc. Phys. Soc.*, London, Vol. XIX, 1904.

A. E. Kennelly—" High-Frequency Telephone Circuit Tests," *Proc. Int. El. Congress St. Louis*, Sec. G, Vol. III, pp. 414–437, 1904.

Béla Gáti—"On the Measurement of the Constants of Telephone Lines," *The Electrician*, Nov. 2, 1906.

B. S. Cohen and G. M. Shepherd—" Telephonic Transmission Measurements," *Journ. of Proc. Inst. El. Engrs.*, London, Vol. XXXIX, p. 503, 1907.

Béla Gáti—"Uber die Anwendung hyperbolischer Functionen auf weite Entfernungen wirkenden Telegraphen- und Telephonenströmen." *Electrotechnik und Maschinenbau*, Vol. 33, 1910.

K. W. Wagner—" Uber die Frequenz der Fernsprechströme," *Elektrotechnische Zeitschrift*, 1910.

J. A. Fleming—" The Propagation of Electrical Currents in Telephone and Telegraph Conductors," Constable & Co., London, May, 1911.

F. Breisig—" Uber die Energieverteilung in Fernsprechkreisen," *Elektrotechnische Zeitschrift*, June, 1911, Vol. XXIII, pp. 558–561, Vol. XXIV, pp. 590–593.

K. W. Wagner—" Elecktromagnetische Ausgleichsvorgänge in Freileitungen und Kabeln," *Elektrotechnische Zeitschrift*, 1911, pp. 899, 928, 947.

A. E. Kennelly—" The Application of Hyperbolic Functions to Electrical Engineering Problems," The University of London Press, 1912.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 24, 1913.

AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION

BY H. M. FRIENDLY AND A. E. BURNS

In designing the equipment used by the Northwestern Long Distance Telephone Company, operating a toll system connecting independent local telephone exchanges in Western Oregon and Western Washington, the first consideration was to improve the traffic capacity of operators, lines and equipment. Incidental to this was the desire to render the work of the operator more mechanical, so that the personal equation would be eliminated as far as possible in the handling of switching equipment. To this end, somewhat radical and seemingly complicated electrical circuits were resorted to in accomplishing complete, positive lamp supervision, and in meeting various traffic requirements and expedients, but as long as such departures from common practise meant simpler operating, more rapid switching, or increased transmission efficiency, all consistent with reliability and normal maintenance, the means were considered as fully justified.

The fact being that the Northwestern Long Distance Telephone Company has no direct authority over its connecting companies, the inability to enforce discipline and strict traffic rules over foreign operators had to be taken into consideration, and every possible step employed to improve and quicken the service in order to counteract this deficiency, competition for business being very keen.

It will be observed that the equipment on the toll switchboards, proper, is free from special, irregular or complicated devices that require great care and special instruction for proper operation—that the circuits are uniform at all operators' positions—

that the minimum of apparatus subject to adjustment is employed in the switchboard; such apparatus, wired in sets, being placed in the wirechief's room, or in any other place where it may be convenient for inspection and repairs, without in any way interfering with or annoying operators at work. Further, the apparatus-sets have been mounted in detachable units, thus allowing a complete change of the character or type of equipment associated with any line without altering or mutilating wiring in the apparatus-set. Each detachable apparatus-set consists of a frame $\frac{1}{8}$ by $\frac{3}{4}$ by $\frac{3}{4}$ in. (3.1 by 19 by 19 mm.) angle iron, bent to form three sides of a rectangle 5 by 16 in. (12.7 by 40.5 cm.), the top being left open. A piece of 24-gage sheet iron is riveted to the back to form a dust-proof, induction-proof case, and a close-fitting sheet iron detachable cover is provided for the front, it being found that where the apparatus sets are mounted close together (6-in. or 15-cm. centers) without cross-talk protection, when relays of one set were being operated, induced clicking noises could be heard on the lines associated with the nearby apparatus sets. The top of each apparatus-set frame is closed by a piece of the same angle iron, bent and pivoted to form a sort of rocking switch carrying eleven insulated points used as terminals; these points are made to engage with insulated companion springs or clips on the stationary rack, the latter being of 3/16 by 2 by 2-in. (4.7 by 50.8 by 50.8 mm.) angle iron. All external wires are brought to the rack clips permanently; thus to remove an apparatus set, and substitute another, it is only necessary to disengage the clips, unhook the set from the rack, place the desired set on the rack and tilt the rocking switch so its points engage their companion rack clips. All wiring of the sets is brought out to the rocking switch, the wiring having extra heavy braided insulation, and so disposed loosely in the set that it is not injured by the small hinge movement of the rocking switch in cutting the set in or out of service. The detachable feature of the apparatus-sets allows such equipment at distant offices to be removed and sent to the shop for repairs or alterations in specially designed shipping boxes, avoiding the necessity of sending out a high-priced man and paying the incidental cost of transportation, etc. The expense of one such trip alone to some of the distant offices would more than pay the cost of a duplicate set to be kept for such emergencies. An operator, or any inexperienced person, can easily effect a change of sets, place the displaced set in the special box and express it to the shop.

The relays used in the apparatus sets are mostly of the automatic vertical type. This type was chosen because of its adaptability, almost any circuit combination desired being possible by merely assembling the proper springs and insulating bushings. The contacts can be given any reasonable degree of tension or pressure, and the slight sliding movement due to construction tends to keep the contact surfaces bright and free from dust. The margin of adjustment in this type of relay is also very wide, and all parts are easy of access for inspection and maintenance. These relays are mounted upon angle-iron shelves, pivoted in the apparatus-set frame in a manner similar to the switch at the top, allowing all the wiring and relays to be tilted out, inspected and repaired without removing them or mutilating the wiring. A gravity-catch locks the relay mount in place when tilted back into normal position. The repeating coils, retardation coils, condensers, etc., associated with the apparatus sets are mounted on the back thereof, since there are no moving parts to inspect or adjust.

Another type of relay that has proved its usefulness and reliability is a polarized relay designed expressly on the plan of a polarized ringer, and which is compact and extremely sensitive, though capable of withstanding abnormal currents without impairing its adjustment—such as 20-cycle ringing power. This relay is also mounted as a part of the apparatus-set, on a pivoted shelf, when the equipment comprises such a relay.

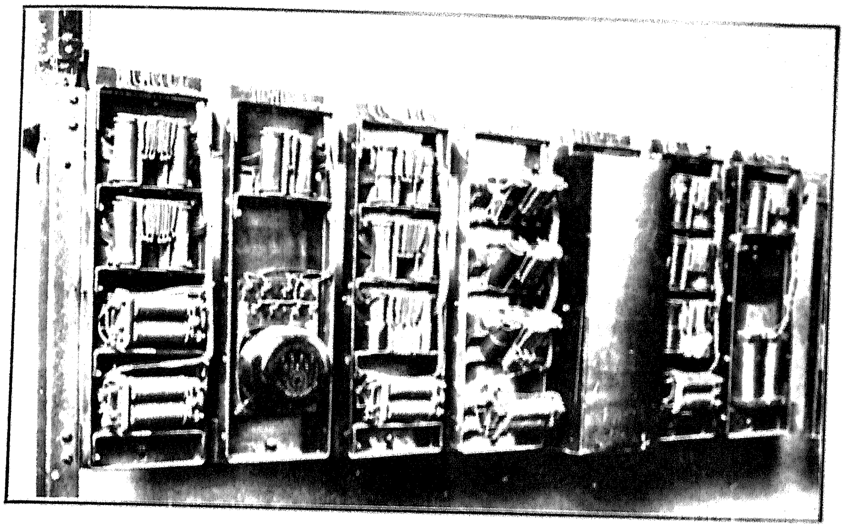
The apparatus sets are secured to the rack by slots which slip over the heads of round-head machine screws on the rack angle iron, the slots being enlarged at the bottom to take the heads of the screws.

One of the first conditions to be surmounted was in the territory between Portland and Tacoma, a distance of 145 miles (233 km.). From Portland north to Centralia, a distance of 95 miles (152 km.), is a No. 10 B. & S. copper circuit, used as a way-line on which are ten stations and offices, each with a 1600-ohm signal (switchboard drops and bells having the same type of movement) having a two-microfarad condenser in series therewith (this latter provision is carried throughout the entire system to facilitate line testing and fault location). From Chehalis, 4 miles (6.4 km.) south of Centralia, to Tacoma, a distance of 50 miles (80 km.), is a similar way-line on which are ten stations. Thus the way-lines lap for a distance of 4 miles (6.4 km.) between Centralia and Chehalis. This lapping was done because these towns are the largest between Portland and Tacoma, and

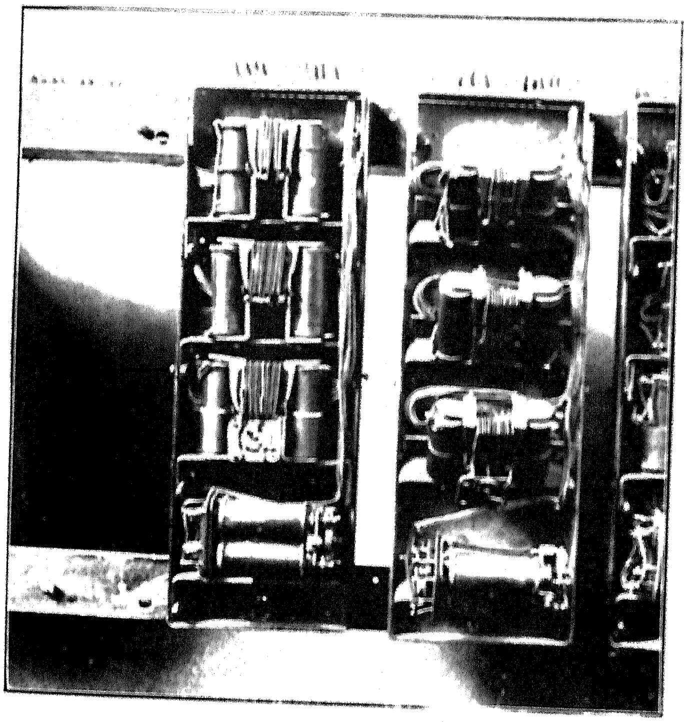
incidentally are about equal in importance from a traffic standpoint from both directions. The lapping of the circuits obviates delays such as would ensue if intermediate switching had to be resorted to. For normal switching between Portland and Tacoma, and Portland and Seattle, the latter 40 miles (64 km.) north of Tacoma, through trunk lines were provided. However, it is often desired to press into requisition the two way-lines above mentioned for Portland-Tacoma traffic. Any intermediate traffic is handled over these way-lines, excepting rush calls when the way-lines are busy. Two No. 10 B. & S. copper way-lines are provided in addition to the above, between Portland and Castlerock, a distance of 62 miles (99 km.) north. These lines are equipped for calling direct into the local automatic exchange at Portland. The methods used will be explained further on.

Delays in the establishing of, and in the taking down of switching connections manually at Centralia or Chehalis for such through traffic led to the equipment of the way-lines for performing this function of interconnection and disconnection remotely, from either Portland or Tacoma, under the instant automatic control of the operators—day or night. The electrical circuit accomplishing this is shown in Figs. 1 and 2, and later described. The operating specifications of the through switching circuit are as follows:

The lines are normally used as way-lines without any restrictions whatsoever. Assuming that Portland desires to communicate with Tacoma—bear in mind that the switching and line equipments at both Portland and Tacoma are identical (excepting that battery on relay *D*, Fig. 1, is reversed at Tacoma as indicated in the diagram), and similarly operated, and that the equipment at Centralia for effecting the interconnection (obviously this equipment could have been installed at Chehalis, or even on a pole between the towns, with the same effect) is actuated from either Portland or Tacoma—first the Portland operator ascertains if the Portland-Centralia line is busy by listening-in on the line. If not busy, the operator withdraws the plug from the regular jack and inserts it into the jack following, which may be called the through switching jack; over the latter jack is a number designating the remote line. Inserting the plug into the through switching jack causes the equipment at Centralia to be actuated, connecting the lines together, so that the Portland operator by listening-in can instantly know if the remote line is idle, and that without any disturbance to possible



VIEW OF PORTION OF RACK SHOWING APPARATUS SETS
No. 4 has relays tilted out for inspection. No. [illegible] set with [illegible] in place



VIEW OF TWO APPARATUS SETS
Set to the left has been removed to show springs at [illegible] which engage with points of the [illegible] switch at [illegible]

users on the remote line. If the remote line is found idle, the Portland operator rings Tacoma's signal, or the signal of any office on the remote line, in the usual way, with her regular cord-ringing-keys, no special keys or devices being employed. Since no bell on the near line rings from the through switching jack, the same code of signals has been used on the near and remote lines, so far as was found convenient. Incidentally, the signal showing at Tacoma in the above instance is above the through switching jack, indicating that the signal comes from Portland. The object of this will be shown later. If an intermediate office on the near line desires Tacoma, for instance, such office rings Portland in the usual way and requests Tacoma. The Portland operator, acting as a through operator, removes her plug from the regular jack and inserts it into the adjacent through switching jack, and if the remote line is found idle, signals as above. As no ringing impulses are projected on the near end, from the through switching jack, an operator listening in at the intermediate office hears no disturbance. When Tacoma answers the signal corresponding to her through switching jack, the Portland operator can leave the line at once, as Tacoma's plug being in the through switching jack, maintains the through connection. If the call cannot be completed at once, Tacoma signals the calling office over her through switching jack when ready; Portland pays no further attention to the call, and makes no note of it, since Tacoma is a checking office. If, however, an intermediate office on the remote line is desired, the Portland operator supervises and checks the call as if it were a through switch made manually at Portland, which, from an operating standpoint, it is. Tacoma in the latter instance would ignore all signals for intermediate stations coming in on the signal associated with her through switching jack, knowing that Portland, a checking office, is supervising such switches, although Tacoma checks all signals for intermediate stations coming in on the regular line signal.

The electrical details are as follows:

1. The Portland operator plugs into the through switching jack, projecting battery current out on the line and operating the relay at Centralia, cutting the lines together.

2. The operator rings on the through switching jack, which operates a relay in the apparatus-set that reverses the battery projected out on the line. This reversed battery operates a polarized relay at Tacoma, and throws 20-cycle ringing power back on the remote line, the relay at Centralia simultaneously

breaking the line connection during the time the current is reversed.

3. When the ringing key is released, the current is restored to the original direction, the relay at Centralia operates, and the through talking circuit is re-established.

4. When the call is completed the operator withdraws her plug, and the lines are restored to their normally separate condition as far as speech is concerned.

Referring to Fig. 1, at the top of this diagram are the eleven

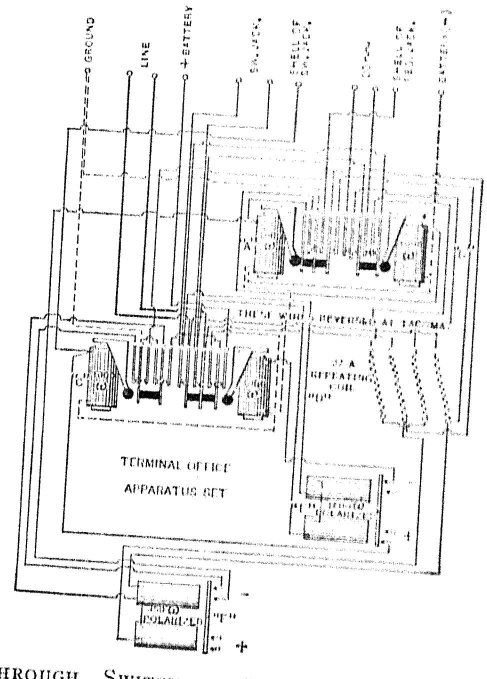


FIG. 1—THROUGH SWITCHING CIRCUIT—TWO-WAY—RING-BACK (SEE FIGS. 2 AND 10)

insulated terminal points carried by the rocking switch at the top of the apparatus set. The companion clips at the top of the rack are connected as shown: No. 1 to main ground; No. 2 and No. 3 to the two wires extending to the line and to the spring jack and drop associated with the line. No. 4 is connected to a set of batteries, in this case dry cells having the negative or zinc pole grounded; No. 5 and No. 6 are connected to the through switching jack and associated signal; No. 7 with the shell or "relay wire" of the through switching jack; No. 8 and No. 9

to 20-cycle ringing power; No. 10 to the shell of the regular line jack; and No. 11 to the main storage battery having the positive pole grounded.

Tracing a particular call, say from Kelso on the Portland way-line to Yelm on the Tacoma way-line, and knowing the modus operandi of the call from the preceding paragraphs, we can follow the action of the relays shown in Figs. 1 and 2. When Kelso rings, the Portland signal associated with the regular line jack is actuated, the jack and drop of the through switching line being unconnected. Portland answers by plugging into the regular line jack, ascertains that Yelm is wanted and changes the cord plug to the through switching jack. The third or shell wire of this plug is grounded, and engaging the shell wire of the through switching jack, throws a ground through point No. 7

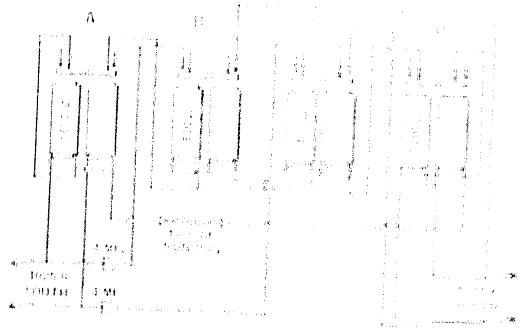


FIG. 2—THROUGH SWITCHING CIRCUIT, CENTRALIA, WASH. (SEE FIGS. 1 AND 10)

of the apparatus set and actuates relays C and D, Fig. 1, also actuating the cut-off relay associated with the through switching jack. Relay D connects the switching jack to the line, and in conjunction with relay C projects battery current to the center of relay F, where it divides and finds its way through the coils of relay F, through two windings of the repeating coil to the line. Following the line to Fig. 2 (Centralia) the battery current flows through the coils of relays A, B, and C, dividing again through the coils of relay D to reach the Tacoma way line. The apparatus set at Tacoma is identical with Fig. 1, except, as may be noted, that two of the wires are reversed on relay D so that the batteries at Portland and Tacoma will not be opposed when operators have cord plugs in their respective through switching jacks, and the current for ringing control is

necessarily of the opposite polarity. Following the line to Fig. 1 again, this time at Tacoma, the current can be traced through the repeating coils and the coils of relay *F* to ground, whence it returns to the battery at Portland. The current thus established flows on the line from Tacoma to Portland, and relays *B* and *C*, Fig. 2, are wired to operate with this direction of current, connecting the two way-lines together through two four-microfarad condensers. Relay *F* at Tacoma operates to the minus side, and thus produces no effect. When Portland rings, relay *E*, which is bridged across the line, vibrates and thus keeps the contacts practically wide open, the period of contact being of short duration. This allows relay *D*, which has a strong tension, to fall back, and tracing the circuit as before, with relay *C* actuated and relay *D* normal, plus battery current from point No. 4 of the rocking switch is finding its way to the line and through the sets at Centralia and Tacoma as before, but this time the current flows in the reverse direction, from Portland to Tacoma, actuating relays *B* and *C* at Centralia in the plus direction and breaking the talking connection. Relay *F* at Tacoma is also actuated in the plus direction and actuates relay *A* which in its turn actuates relay *B*. Relay *B* impresses 20-cycle ringing power on the through switching jack, and actuates the associated line signal, apprising the Tacoma operator that Portland is ringing, and not some intermediate station, the regular line signal not being actuated, since relay *A* grounds the shell of the regular line jack, and operates the cut-off relay associated with this jack. Relay *B* also impresses 20-cycle ringing power on the primary winding of the repeating coil, and as relay *A* has short-circuited the inner lugs of the secondary winding, 20-cycle ungrounded ringing power is thus projected out on the line. This is important, as the normal ringing power is grounded on one side, and if thrown directly on the line would shunt out a large portion of the operating current, while the alternating current from the live side of the ringing generator would return to ground through the relays of the set, vibrating them and thus breaking up the ringing impulses projected out on the line. Also, grounded ringing power or ringing power subject to grounds from intermediate stations, must be guarded against, otherwise the switching relays at Centralia would operate, cutting the lines together, interfering with service; while the relays at the terminals would operate the switchboard signals and also ring back on the line. This is prevented in two ways.

1. In Fig. 2, the line circuit is carried through the contacts of relays A and B before reaching the windings of relays B and C, the switching relays, and any ringing currents on the lines will open these contacts, preventing any ground leakage from operating B or C.

2. In Fig. 1, relay A operates with a ground from relay F, and the former in its turn operates relay B. The interval of time necessary to accomplish this being comparatively long, ringing impulses of any ordinary frequency will not endure long enough to complete the series of operations. It will be noted, however, that the intermittent ground from the contact of relay F is passed on from relay A to relay B. If the main ground were independently wired to the contacts of each relay it would have the opposite effect, that of producing a steady action of relay B by the intermittent action of relay F. Of course, this could be obviated as in composite telegraphy, by using a howler or high-frequency ringer, or by the use of repeating coils at these stations, but this would increase the amount of equipment in the aggregate to more than is required in these sets to prevent the trouble. The endeavor has always been to keep unnecessary or avoidable equipment off the line at points where there is no competent man to maintain it. As used, the three apparatus-sets can be disconnected from the lines if desired by pulling the switches at the top of each set, and not only will the normal operation of the lines be unaffected by the change, but no extra apparatus will be left on the line at any of these offices. Conversely, all of these apparatus sets may be regarded as supplementing the regular line equipment, and any facility they may afford in operating may be regarded as that much clear gain.

In the case of the above through switching circuit, ringing power is projected back from the opposite terminal office, since no ringing power is available at Centralia. If such ringing power were available, it could be used to ring in both directions under the control of the terminal offices, in lieu of the method used. The manipulation of the circuit would be the same in either case, as far as the operators are concerned.

A condition in a way similar to the one first described between Portland and Tacoma existed between Portland, and Dallas and Independence via Salem, the latter being 52 miles (83.6 kg.) (No. 10 B. & S. copper) south from Portland, and 15 miles (24 km.) (No. 10 B.w.g. iron) east from Dallas, Independence being

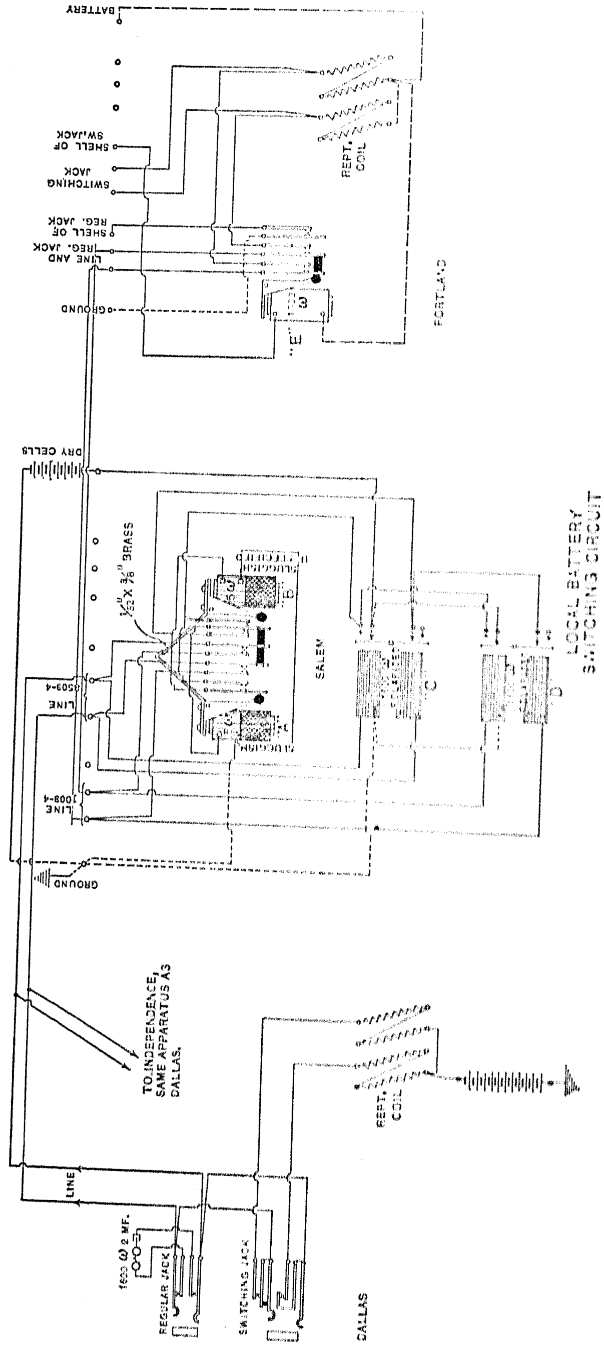


Fig. 3—Local Battery Through Switching Circuit (See Fig. 10)

on a leg from the latter line. The circuits (see Fig. 3) were somewhat modified by reason of the fact that, due to the small number of stations involved, and the short distance, it is found possible to ring through directly from any office on the line. In this circuit means are provided at each switching station whereby the operator by plugging into the through switching jack causes battery current to be projected out by the line. This battery current serves to operate the through switching relays at Salem which connect the two lines together for talking. Ringing is done directly in the usual manner, and at the termination of the call, the switch is released on the removal of the cord plug from the through switching jack. Two jacks are provided at both Dallas and Independence (see Fig. 3), one the regular line jack, used for normal manual switching, and a through switching jack, provided with extra contacts for connecting the split retardation coil to the line. The center of this coil is connected to battery, the current following the line to Salem and operating the switching relays.

A similar action takes place at Portland, where the retardation coil is connected to the line by means of relay *E*, which is operated from the shell of the through switching jack, projecting current on the line and operating the switching relays at Salem as before. Also, if Dallas, Independence and Portland should all plug into their respective through switching jacks simultaneously, the same effect would take place, the currents from the different sources merely aiding each other after the connection is established at Salem. The operation of the apparatus set at Salem is on the plan of a mechanically locking relay, which locks the lines together when actuated by relays *C* or *D*, Fig. 3. This relay is operated by six dry cells, and for economy in battery consumption is made to disconnect the local battery after locking mechanically. By this means one set of dry cells can be made to supply the necessary current for a number of months, whereas maintaining the locking action by means of current would shorten the life of cells to a few weeks or possibly days, depending upon the amount of traffic. Either relay *C* or *D* operating to the minus side actuates relay *A*, which when closed actuates relay *B*. Relay *A* is now disconnected from the battery on the back contact of relay *B* and, after a slight pause due to its sluggish properties, falls back. It will be seen from the diagram that this mechanically locks relay *B* in the operated position, disconnecting it electrically,

and it remains in this position as long as relays C and D are energized, holding the lines connected for talking and ringing purposes. When the plug is removed from the through switching jack at the calling office, the current ceases to energize relays C and D; and upon one or both of these relays making contact on the plus side, which is in the normal position of the armatures, current again flows through a make contact of relay B, actuating relay A and unlocking B. Upon relay B returning to its normal position the current in relay A is broken, and it too returns to its normal position, when the set is ready for another switch.

Grounded ringing on one line in the normal position of relays A, B, C, and D will not affect the other line, since relay A must pick up, and after that relay B, and the time necessary to accomplish this is found to exceed the duration of an impulse where the ringing frequency is over fifteen cycles per second.

The mechanism used for locking up relay B in this circuit is capable of wide application. By using a heavy momentary current, it is possible to give the relays a heavy contact tension, thereby reducing the liability to get out of order. The fact that the current is but momentary allows dry cells to be used in stations where a storage battery is not available to operate the relays. This form of locking relay can be used at stations on toll lines where it is desired to have a means of cutting a line in or looping it through a station for testing or switching purposes, and yet due to length of cable or other conditions it is impracticable to allow any permanent legs or loops from the lines, the relays being controlled from contacts on the switching jacks in the station equipment.

Many adaptations other than recounted here may be made—such as through switching between any two of three lines where all terminate at one office; switching from either of two lines to either of two lines, where all four terminate at one office; or switching of three lines in tandem through two through offices, etc. In other words, the apparatus-sets described may be modified to satisfy an almost endless number of traffic, operating, or electrical conditions. If it is desired to have lamp signals show over the line jacks at the through office to apprise the through operator that the lines involved are busy by reason of a through call handled remotely, a very simple modification in the apparatus-set at the through office will accomplish it. Further, a lamp signal might be provided at the terminal offices to apprise the operators as to the busy or

idle condition of the remote lines, obviating listening-in to determine it.

Under usual practise, through switching introduces relatively expensive operating methods, due to the fact that more operators and more line circuits are required than to handle the traffic over direct trunk lines, and direct way-lines; thus meaning lower earning efficiency to the operating company and retarded service to its patrons, the latter doubtless having a potent though intangible effect in discouraging business as well. In the first case mentioned, employing usual methods, the Portland operator desiring Tacoma would first be obliged to signal Centralia or Chehalis in the usual way and await the operator's convenience in responding; then tell this operator her wants, and again wait until she ascertained the state of the desired line, and reported back, if busy, thus consuming the time of two operators, and what is of far more moment—the time of the line. An operator establishing her own through connections by remote control avoids such delays—in fact gains all the advantages of direct trunk efficiency between points where the volume of traffic does not warrant the expense of the proper number of trunk lines to carry the maximum or "peak" demand without delaying traffic unduly, or where the advantage of direct trunk or direct way service is desired but not warranted by the traffic offered. The delays experienced in establishing through connections manually at intermediate offices are augmented by the delay in getting the established connection taken down at the termination of the service, or annoyances such as an inadvertent disconnection at the through office. In the remote control method, the withdrawing of the plug by the calling operator instantly disconnects the lines, and not otherwise.

Operators maintain that there is far less nerve strain and fatigue attaching to the remote control method of establishing through switches than with the manual method where the enforced delays under stress are very trying.

In order to facilitate "rapid fire" service between Portland and Seattle, a distance of 185 miles (297.7 km.), an unusual traffic and circuit arrangement was devised. But one trunk circuit was available, a No. 8 B. & S. copper loop having no intermediate offices obtaining service over it, and since many calls to Seattle were special calls or through calls to points beyond, it was necessary that the Portland operator should be able to signal the Seattle toll operator at will in the usual way

without disturbing the Seattle *B* operator. Following the regular line jack on the Portland switchboard is an auxiliary jack that may be called the *B* board jack, which is used when the Portland operator desires to order up a number directly via the Seattle *B* board. The Portland operator upon plugging into this jack is then able to speak directly into the head telephone of the Seattle *B* operator over the regular toll line without further preliminaries, and remains so connected until the *B* operator plugs into the called subscriber's line. Over the *B* board jack at Portland are placed two lamps which indicate by glowing that the Portland operator is not restricted by the Seattle toll operator, and further that she is in connection with the *B* operator's head telephone, and thus can proceed to order up the desired subscriber's line. The extinguishing of the

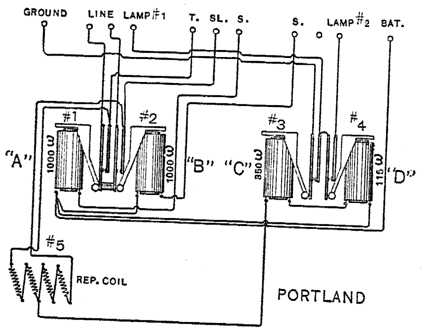


FIG. 4—TRUNKING CIRCUIT FROM TOLL LINE TO "B" BOARD (SEE FIGS. 5 AND 10)

second lamp indicates that the *B* operator has inserted the line or trunk plug into the local line jack. A lamp is placed over the jack of the line on the Seattle toll board, which by glowing indicates to the operator that the line is in use to the *B* board and is cut off at the toll board, the busy lamp being also lighted over the answering jack and its associated multiples.

The principle of operation (see Figs. 4 and 5) is that the Portland operator by plugging into the *B* trunk jack causes battery current to be projected out on the line which operates a relay at Seattle, cutting the line into the *B* operator's head telephone set, whereupon the Portland operator proceeds to ask for the Seattle, local number, just as a Seattle *A* operator would, specifying, however, "on 16," such being the number of the *B* plug associated with the toll line, as otherwise the *B* operator would not know what *B* plug to use.

This cutting into the operator's set is accomplished through the agency of relay *A*, Fig. 4, which is operated from the shell wire of the *B* board jack. The current flows through two relays in series, relays *C* and *D*. Relay *C* is adjusted to operate through a resistance of 4000 ohms, while relay *D* will not operate through a resistance of over 2000 ohms, which gives a margin of adjustment that is used to give supervision in the following manner: If the switching apparatus is on the line, that is, the Seattle toll operator has no plug in the line jack, relays *C* and *D* pick up and light the supervisory and guard lamp associated with the Portland *B* board jack, assuring the Portland operator that she has the circuit to the Seattle *B* operator's head telephone set.

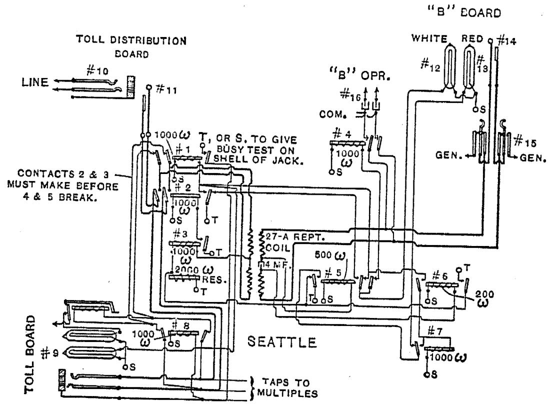


FIG. 5—LINE CIRCUIT— FOR DIRECT TRUNKING FROM TOLL LINE TO "B" POSITION (SEE FIGS. 4 AND 10)

This same current operates relay No. 3, Fig. 5, which controls relay No. 2, a cut-off relay which disconnects the line from the toll switchboard, lighting a lamp over the answering jack and also the associated multiples and thereby apprising the Seattle toll operators that Portland has the line in service via the *B* board. Relay No. 2 also operates relay No. 4 which cuts in on the *B* operator's head telephone circuit. When the *B* operator inserts the trunk plug associated with the toll line into the called subscriber's line, or into a trunk jack to a sub office, relay No. 5 operates, cutting off the *B* operator and lighting the subscriber's supervisory lamp on the *B* board. Relay No. 6 operates when the subscriber answers, extinguishing the *B* supervisory lamp, and locking relay No. 7 in an operated position until the call is released by the Port-

land operator withdrawing her switching plug. Another action of relay No. 5 is to cut the 2000-ohm resistance in series with the line relays, causing relay *D* at Portland to fall back, lighting the guard lamp No. 2 and thus giving Portland notice that the *B* plug has been inserted in the called line. When the subscriber answers and relay No. 6 is operated, this 2000-ohm resistance is short-circuited, causing relay *D* at Portland to pick up again, extinguishing the second guard lamp and apprising the Portland operator that the subscriber has answered. When the Seattle subscriber hangs up, relay No. 6 falls back, removing the short circuit from the 2000-ohm resistance, and causing relay *D* again to light its associated lamp. The clearing signal is not given at Seattle until the Portland operator removes her plug, whereupon relays No. 3, 2, 1, and 7 fall back, and relay No. 5 being operated, causes both supervisory lamps to glow until the *B* operator removes the plug, when all parts of the apparatus return to the normal positions. In this condition the line can be used for normal toll purposes, ringing on the line operating the regular line signals only, the Seattle operator answering the signal by plugging into the line jack and cutting off the trunking apparatus by means of relay No. 8. This cut-off feature gives the Seattle operator an equal chance of securing the line for outgoing business and renders it impossible for the operator at Portland to monopolize the line.

Except that the Seattle *B* operator is instructed to give the direct toll line trunks special attention, there is nothing to distinguish them in supervision from any of the local trunks, but a sounding relay associated with the lamps of the direct toll line trunks which is mounted beneath the keyshelf of the *B* board to aid in attracting the operator's attention to insure the most prompt disconnections.

Similar circuits were used between Tacoma and Seattle, provision being made also for Seattle to call Tacoma subscribers in the automatic exchange by means of an automatic calling device, which is described later in this paper. Calling with an automatic calling device as above has been tested successfully from Seattle to Portland, and there was no electrical reason for not employing it.

If, in calling Seattle numbers directly via the *B* board, the desired party was found to be out, the Portland operator would say, "have him call Long Distance 16." Upon the called party requesting this number of the Long Distance recording operator at Seattle, she understood that the call had originated at Port-

land, and after so informing him, obtaining his number, etc., would notify the operator on the Portland line who in turn notified Portland, who would complete the call via the *B* board.

Since the Northwestern Long Distance Telephone Company connected with the local automatic exchange of the Home Telephone and Telegraph Company of Portland, and local automatic exchange of the Puget Sound Home Telephone Company at Tacoma, before the latter was absorbed by the Sunset Telephone and Telegraph Company, this offered an opportunity to improve the service to those cities by permitting distant connecting exchanges on the system of the long distance company to call subscribers at Portland and Tacoma by automatic means. It was decided at the outset that to insure satisfactory operating and traffic results, the normal uses of the lines so equipped must not be restricted in any way—that is, it must be possible to signal the toll operator at the city having the automatic local exchange in the usual way from offices on the toll line, and vice versa. Also that means be provided on the toll board for checking, supervising, and listening-in on all switches called directly from the distant office, to insure proper timing of service and handling of lines, and proper discipline, the latter being important for the reason that called local subscribers assume that the operator is also local, and would censure the toll company for any breach on the operator's part, it being remembered that the distant operators are not in the employ of the toll company. Further, that no call into the automatic exchange should be possible without the toll operator of that city being immediately apprised (by means of lamp signals above the line jack) of the attempt to call, and of the response of the called local subscriber.

At the distant office two spring jacks (see Fig. 6) are provided; one for normal switching, having a signal associated therewith; the other an auxiliary jack, being used for automatic calling only. The operator first ascertains by listening-in on the regular or normal jack if the line is idle (if a way line), and then withdraws the plug and inserts it into the auxiliary jack and proceeds to "dial" the number without further preliminaries. On the completion of the dialing, two impulses are made by calling the digit "one" twice in quick succession, which rings two short bells at the called subscriber's telephone in the automatic exchange. It has been found that this method of ringing is more convenient than to ring with the regular cord-ringing-key. However, by

the introduction of an additional relay (as *E*, Fig. 1) in the apparatus set at the calling office, such cord-key ringing may be effected. In such case the distant office would ring the local subscriber in the automatic exchange in the same manner as in ringing on a direct line. The automatic exchanges referred to are what is known as the "three-wire" Strowger system, thus necessitating the use of a ground in connection with the two line wires to effect a call. In the first experiments looking towards the use of the automatic feature on the toll lines, the three-wire principle was adhered to, and gave satisfaction on those lines serving the two terminal stations only as trunk lines, but where three or more stations were served it was seen that to keep the two wires from any loop connections would involve too many complications in station equipment. Another thing that rendered the three-wire circuit on the toll line end practically out of

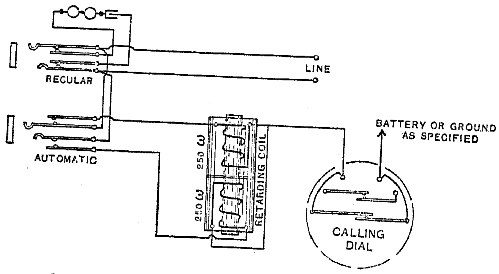


FIG. 6—CALLING OFFICE CIRCUIT, AUTOMATIC (SEE FIGS. 7 AND 10)

the question was that any kind of ringing current used for signaling between stations would vibrate the relays of the apparatus-set and cause a great deal of trouble in the automatic exchange. Due to the operating conditions of the three-wire automatic system, this would be certain to cause a great many cut-offs and extraneous noises on other lines in the local automatic exchange. The so-called "two-wire" system of calling was therefore adopted, with the necessary modifications to translate from the two-wire system on the toll line to the three-wire system on the local automatic exchange. The only difficulty met was due to the fact that in this system the connector or last switch of the series involved in making a call in the local automatic exchange drops back if the line called happens to be busy; a "vertical" impulse following, which would ring on the called line if it had been selected, serves to step the connector "off normal" and automatically gives the busy tone to the calling

party. If, however, the "vertical" impulse were followed by a "rotary" impulse, the connector would again step up and another vertical or series of vertical impulses followed by a rotary impulse would select one of the one hundred lines served by this connector, and ring some subscriber—almost certainly the wrong one. To guard against this, two different types of repeater apparatus-sets, or translators, were developed; one depending upon a small step-by-step mechanism (see Fig. 7) similar to that used in the automatic system in meter switches, and the other (see Fig. 9) depending upon a polarized relay being actuated by the proper polarity from the calling station, to eliminate the rotary impulses after the subscriber's number has been selected.

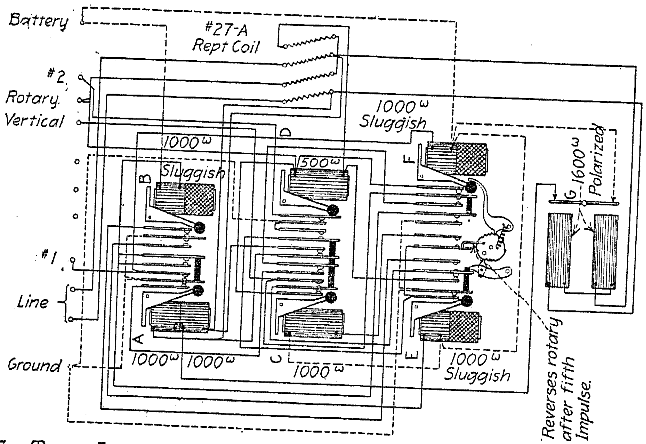


FIG. 7—TOLL LINE AUTOMATIC APPARATUS SET—REVERSES ROTARY ON FIFTH IMPULSE (SEE FIGS. 6 AND 10)

The first method is the one used in the circuit shown in Figs. 6 and 7. In Fig. 6, the two line wires are connected to a double-wound retardation coil, from the center of which the circuit can be traced through the contacts of the calling device (normally closed) to grounded battery, or if desired, to ground direct. To trace a call on these circuits, take for instance a station having the calling device grounded, and of course having battery current on the repeater (Fig. 7); normally none of the calling station apparatus is connected to the line, and it is only when the calling operator plugs into the automatic jack that it is so connected. If the toll line is free, the desired local number is obtained by rotating the calling device successively according to the digits (and letter prefix corresponding

to a digit) of the subscriber's number. If the digit 5 is called, for instance, the ground will be interrupted five times in quick succession by the calling device, after which a comparatively long pause follows while the operator is preparing to "dial" the next digit. It is this prolonged pause which is utilized to give the rotary necessarily following each digit in the three-wire system.

After the number has been selected, ringing, as before stated, is accomplished by calling two digits 1 on the calling device, giving a distinctive double ring peculiar to "Long Distance," the toll operators at the cities mentioned using a similar code in ringing subscribers. If the subscriber's line is busy the busy tone apprises the calling operator of the fact. If the called party answers, the call is handled in the usual way, and upon completion the apparatus is released by the calling operator merely withdrawing the plug for a second, after which the line and equipment is ready for another call. Fig. 7 is a set similar to that in Fig. 1, previously described, having point No. 1 grounded, Nos. 2 and 3 connected to the line wires, No. 4 to a lamp associated with the answering jack of this line, Nos. 8 and 9 to the vertical and rotary wires, respectively, of a trunk terminating in a "first selector" in the automatic exchange. No. 10 is wired to a second lamp associated with the answering jack, while No. 11 is main battery as before. The ground which was traced to the line wires in Fig. 6 may be followed through the two windings of the repeating coil, through the double-wound relay *A*, through the contacts of relay *G* to battery. Relay *A* lights lamp No. 1, which apprises the operator that a call is about to be made, also operates relay *F*, which cuts in the trunk to the automatic exchange and throws a ground on the fourth spring of relay *A*. When the calling operator manipulates her calling device, the line circuit is broken a number of times corresponding to the digit or letter called. Relay *A* falls back with each impulse and "repeats" each impulse to the vertical wire of the trunk, and also causes relay *B* to pick up, which in its turn operates relay *E*. Both *B* and *E* are sluggish relays, having a short-circuited winding or a heavy copper cylinder on one end of the core, and therefore do not fall back in the short interval between impulses, but do fall back in the longer interval between the various series of impulses corresponding to the several digits; first *B* falling back, then after a short interval, *E*. Tracing the circuit, with *E* picked up and

B in the normal position, there is a ground on the rotary side of the trunk, which serves to give the necessary rotary impulse at the end of each series of vertical impulses corresponding to the digits called. Each time relay *E* picks up, it steps up the small ratchet wheel shown in Fig. 7, the steps being held by a pawl controlled by relay *F*. Each number of the automatic exchange is composed of five digits, as *A*1000, *B*1900, *C*3211, etc., and this wheel is adjusted to complete the contact of the spring actuated by it at the completion of the fifth rotary impulse. This operates relay *C*, which reverses the automatic trunk, and disconnects the vertical impulses coming from relay *A*. When the calling device is again operated, this time to ring the subscriber, the same sequence of relay actions takes place as before, but as the vertical impulses are disconnected, the "automatic trunk" leading to the local automatic exchange is not affected until the rotary impulse, and, the trunk being reversed, this is thrown on the vertical side of the trunk, ringing the subscriber, or if the line is busy, stepping up the connector switch to "off normal," and giving the characteristic busy tone. Upon the subscriber removing the receiver, battery and ground are thrown back on the trunk from the connector switch, operating relay *D*, which lights lamp No. 2, and apprises the checking operator on the toll board that the conversation is about to begin. When the call is completed and the calling operator removes her plug, relay *A* falls back, *B* and *E* picking up as before. After about one-half second, relay *F* falls back and disconnects the ground which operates *B*, consequently, *B* falls back, followed by *E*, giving a rotary impulse as before. With *F* in a normal position, however, the automatic trunk is short-circuited, and this causes the rotary impulse to give the "short and ground" necessary to release a call in the three-wire Strowger system.

The reason the trunk is reversed instead of the rotary being merely disconnected after the fifth rotary is that a false ring would be given on release, before relay *F* fell back and released the call, thus calling the subscriber back to the telephone on a false call. Also, in case the calling operator discovered that a wrong number had been called, it would be impossible to release without giving a like false ring, all of which would not add to the prestige of the automatic system.

As stated before, grounded ringing power, or ringing power subject to grounds, must be guarded against when the switch is not in use, and this is accomplished by means of relay *G*, a

polarized relay bridged across the line. When ringing impulses come in over the line, this relay vibrates, and keeps relay A from securing enough current to operate.

It will be noticed that lamp No. 1 flickers with each impulse from relay A, and these interruptions could be utilized to operate an indicator over the answering jack, or tape register if it was considered advisable for the sake of convenience in checking calls.

In the automatic apparatus set previously described (Figs. 6 and 7), the step-by-step mechanism is utilized to eliminate the rotary impulse after the fifth digit is called, but in the repeater set about to be described (Figs. 8 and 9) a reversal of the polarity or direction of the current is depended upon to accomplish the same result. The latter method has the advantage of a more positive ringing

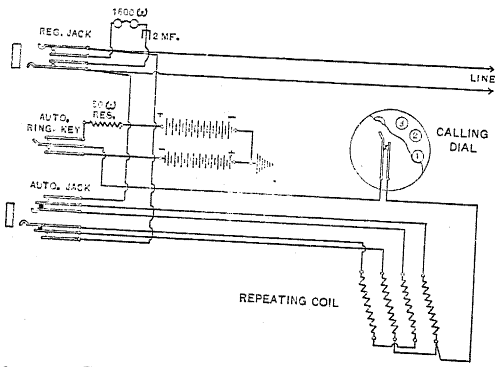


FIG. 8—AUTOMATIC CALLING CIRCUIT — CALLING STATION APPARATUS FOR POLARIZED RINGING (SEE FIGS. 9 AND 10)

control, but has the disadvantage of requiring battery current at the calling station: minus polarity for calling, and plus polarity for ringing the subscriber. While the first set described required a step-by-step mechanism, the latter requires additional relays, which, although not complicating the action of the set, still take up considerable extra space. Where the calling station has no battery supply, the former is the only choice; where battery is available, the choice is about even between the two systems, with a slight preference for the second type on account of its more positive action. The operations of calling are identical and will not be gone into in detail, but to ring the subscriber, the calling operator, using the latter circuit, depresses a self-restoring key associated with the calling device, which reverses the polarity of the battery, as can be seen

by tracing Fig. 8. This ringing of the called party in the distant automatic exchange could be accomplished by introducing a relay similar to relay *E*, Fig. 1, at the calling office, and using the usual cord ringing key.

The functions of relays *A*, *B*, *C*, *D*, *E*, and *F*, Fig. 9, in calling are practically identical with the functions of the similar relays in Fig. 7, and can be followed by reference to the preceding explanation of that circuit. The only difference is that the controlling relay *F* is operated by the polarized relay *G* (Fig. 9) which

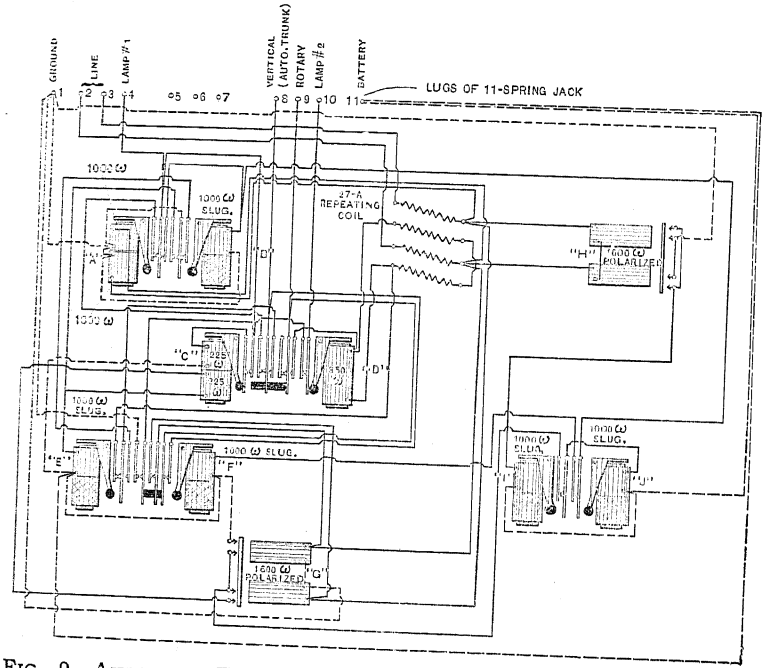


FIG. 9—AUTOMATIC TOLL LINE REPEATER APPARATUS-SET—POLARIZED RINGING CONTROL (SEE FIGS. 8 AND 10)

operates in the minus direction when actuated by the calling current. When the current is reversed by the ringing key at the calling station, relay *G* operates in the plus direction, operating relays *E* and *C*, the latter locking itself during the remainder of the call. Relay *A*, not being sensitive to directional currents, remains actuated and consequently relay *B* does not pick up. In this position, with relay *E* actuated and relay *B* normal, the rotary side of the trunk would be grounded but for the fact that relay *C* has reversed the trunk, throwing this ground on

the vertical wire instead, ringing the subscriber. The impulse wire from relay *A* is disconnected for the prevention of false rings, and local supervision by means of relay *D* and lamp No. 2, and the release at the termination of the call, are all accomplished in the same manner as shown in Fig. 7, and need not be detailed again.

In guarding against grounded ringing, it was found that on account of the extreme sensitiveness of relay *G* (Fig. 9) to such disturbances it was necessary to bridge polarized relay *H* across the inner terminals of the repeating coil and wire it in such a manner that any ringing currents from the line would vibrate its armature, actuating relay *I* and disconnecting the set from ground, preventing the abnormal currents from causing any trouble. In Fig. 7, it will be observed, a single polarized relay was sufficient for this, and the additional relay *I* (Fig. 9) was only added after it was found advisable for the sake of additional positiveness of action.

It will be observed that any accidental ground on the line will not cause a permanent "off normal," as is the case with local lines in the three-wire system, since the automatic apparatus in the local exchange returns to normal upon the ground clearing, by means of a release action in the apparatus-set. This is particularly fortunate, since long, exposed toll lines are always subject to accidental contacts of this nature.

One valuable feature in these repeaters is that any number of stations on the line may be equipped with automatic calling devices, or the more important ones may be thus equipped, and the rest allowed to operate on the line in the normal way only. Thus the ordinary operation and efficiency of the line is not affected, the automatic feature being simply an added convenience and time saver to the stations employing it.

The toll operator endeavors to check closely and time all switches called directly by automatic means by the distant operator, but in the event of heavy traffic on other lines under her care, can ignore the automatic lines and still not lower the standard of service to patrons, as no calls are retarded and the distant operator at the calling office is led to assume that her operating is being constantly supervised.

A vital condition manifesting itself in long-distance automatic operation, which does not occur in local automatic operation, is that to insure quiet long-distance lines it is necessary to introduce a repeating coil in the circuit between the long-distance

line and the local automatic equipment, that is, in the repeater apparatus-set. Also, to insure that impulses from the long lines shall be of the character to properly actuate the switch apparatus in the local automatic exchange, some method of adapting such impulses coming from the long lines to the adjustment used for the short local lines must be provided. This is done in the repeater relays contained in the apparatus-set. It is found in practise that permanent adjustments can be made so that changes are rarely necessary, even for great differences in line leakage—such as from dry to heavy weather.

The longest line equipped for automatic operation is from Corvallis to Portland, via Albany, a distance of 96 miles (154 km.). Albany also obtains automatic service over the same line to Portland. The line is No. 8 B. & S. copper to Albany, a distance of 84 miles (135 km.), and is No. 12 B. & S. copper from Albany to Corvallis, a distance of 12 miles (19 km.).

In the circuits used, both limbs of the line have been reserved for signaling and controlling the various circuit changes. However, the circuits have been designed to admit of ready change so that only one limb of the line would suffice, allowing the remaining limb to be used for telegraphic service if desired. Modifications may be made to permit the operation of phantom circuits as well.

At Portland and Tacoma a distributing board (Fig. 10) is provided for the convenience of the chief operator, permitting the answering jacks to be re-arranged for night switching or for the distribution of traffic, the lines on the multiples remaining permanent.

Supplementing the automatic and remote control methods in connection with toll lines, conveniences have been provided to facilitate the general operating as far as possible, so that the least manual effort is required in handling traffic. Such saving not only conserves the operator's time, and speeds up switching and service, but it greatly conserves the time of toll lines—the operating company's only stock in trade. At Portland and at Tacoma, the company's largest offices, call wires are provided from all operator's positions to all operator's positions. Listening keys cut off all listening keys on the cord sets ahead, so it is impossible to cut two conversations together by accidentally getting two listening keys thrown, and thus demands less attention and care on the part of operators. At the right of the cord listening keys is the supervisory key with a position call wire

lamp associated therewith, the relay controlling the lamp being mounted on the under side of the keyshelf, so that the closing of it will make enough noise to quickly attract the attention of the operator to the signal. Should the called operator be listening to a conversation at the time, she throws the supervisory key cam to the front position, which places her in connection with her call wire, cutting off the cord listening keys, and when through she returns it to the center position, when she is again supervising the cord conversation—the cord listening keys not having been disturbed. The rear position of the super-

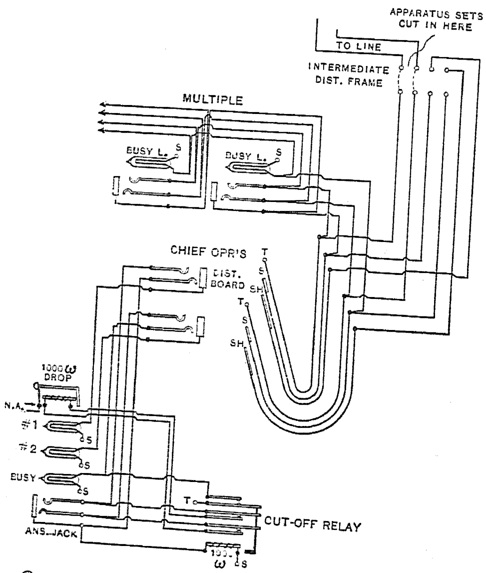


FIG. 10—OFFICE LINE CIRCUIT AT PORTLAND AND TACOMA

visory key allows unobstructed listening and talking. The center or supervisory position of the key short-circuits the secondary of the operator's telephone induction coil and cuts in a 3000-ohm non-inductive resistance. Non-inductive resistance is used in lieu of inductive resistance, since the speech may be further attenuated without rendering it unintelligible. It is not necessary to restore a listening key on a conversation should an operator desire to converse with another local toll operator—she simply depresses the corresponding order button, the cord listening keys being cut off by a relay before she gets the order wire connection; this operation being effective regard-

less of the position of the supervisory key. All supervisory circuits are so designed that no noise is discernible to conversers to whom an operator may be listening, from any manipulation of the supervisory key or order buttons. Operators can listen on front or rear cords independently, and that without first restoring the regular cord listening key of the set; that is, the cords can be cut in both directions with the normal listening key thrown to the listening position.

Reliability of action has been a first consideration in devising the equipment described. Although a circuit in which a number of functions are combined in one relay may look simpler in the circuit diagram and may even have a lesser first cost, by providing several relays with simpler and more positive action the reliability of the apparatus may often be increased and maintenance reduced.

In dealing with local exchange equipment the increased first cost due to elaborate equipment would be a fatal condition where the revenue per line is comparatively small, but where long and heavy copper circuits on expensive construction, and the time of operators, are concerned, the revenue running to several dollars per hour, the first cost of an apparatus-set as described constructed on apparently extravagant lines, is a comparatively insignificant percentage of the total investment, and therefore a relatively inappreciable capital charge. Aside from this is the consideration of not only greater service efficiency, but greater traffic efficiency as well; for observations have indicated that the increased traffic possibilities over a given line will show a gain up to 100 per cent, or even more. The use of the automatic devices may thus in instances obviate the first cost of additional outside construction, that would otherwise be called for in handling the traffic offered, together with its increased operating, interest, and attendant maintenance and depreciation charges.

There has always been a great prejudice and conservatism against the use of so-called "complicated equipment" in connection with long-distance telephone lines; perhaps because a service can be maintained without resorting to this. In long-distance telegraph and multiplex telegraph practise, we are accustomed to complicated and sensitive circuits that require conscientious watchfulness by expert attendants. There does not appear to be any well-founded reason whatsoever why equipment, requiring similar attention and equally as complicated, should not be as permissible in long-distance telephone practise

with its costly copper loop circuits, if the introduction of such complexities will facilitate service or traffic over the lines on which it is introduced, or if it will lessen the number of lines or the number of operators necessary to handle a given traffic, or both.

DISCUSSION ON "TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND", (KENNELLY AND LIEBERKNECHT) AND "AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION" (FRIENDLY AND BURNS), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

F. K. Vreeland: In view of what Mr. Colpitts has just said about the values of Tables III, IV and V being computed, not from the actual constants of the line given in Tables I and II, but from empirical constants derived by experiments with the line as a whole, and worked back from Table VIII I, would ask whether he can give us any information as to the agreement of these empirical constants with the actual measured constants of the line?

E. H. Colpitts: The authors give the line constants in the paper. I did not call particular attention to these tables because in the discussion of his results, Dr. Kennelly has not used the electrical constants of the artificial line at 760 periods per sec., in other words, Tables I and II are merely descriptive of the apparatus that he used.

Answering specifically Dr. Vreeland's question, I would say if you assume the "accepted mean values" of Dr. Kennelly, in Table VIII, that is, a surge impedance of $465 \diagdown 11^\circ$ ohms, and a mean section angle of $(0.235 + j\,1.272.)$ are correct, the line must have the following electrical constants at 760 periods per sec.

Effective resistance................119 ohms;
Effective inductance............... 0.0926 henrys;
Effective capacitance.............. 0.670 mf.
Effective leakance.................164 micromhos.

D. C. Jackson: While this desirable and interesting paper relates to a test of an artificial aerial telephone line using currents having a frequency of 760 cycles per second, it is, nevertheless, a paper of just as great interest and significance to the man who is working in power transmission in large bulk as to the man who is working in power transmission in very small bulk; that is, what we call heavy power transmission, on the one hand, and telephone transmission on the other. Of course, when we are working on power transmission in large bulk we are endeavoring to transmit a fundamental frequency, and to eliminate the harmonics. In the case of the telephone, on the other hand, the necessity is to transmit all the harmonics preserved in substantially equal degree over a large range of frequencies.

The significance of this paper, then, is great to both power transmission men and telephone men. One of the important papers that have come before the Institute in relatively recent years is the description of an artificial line which Dr. Kennelly published, I think, a year or two ago in the Institute PROCEEDINGS.

As I understand it, the present paper embodies the results of tests on that same transmission line, and it contains another demonstration that the formulas including the hyperbolic trigonometrical functions are highly accurate for the computation of transmission lines. That has been very well proved previously by actual telephone circuits.

As far as heavy transmission service is concerned, the frequencies are so low and the lines so relatively short that practise has not yet gone far enough to meet a quarter wave length or half wave length in actual practise, but we are surely coming to it, and it is essential that these formulas shall be studied by transmission engineers.

F. K. Vreeland: It is exceedingly interesting to me to note the close agreement between Dr. Kennelly's experimental results and the computed values, though it would be still more interesting if the computed magnitudes were computed from the beginning instead of being worked back from tests on the completed line. As everybody knows who has had occasion to work with questions of line propagation, the artificial line is a very valuable experimental adjunct, but I think, perhaps, we have all felt some doubt as to how closely the predicted results of the artificial line agree with those we get in real practise. Dr. Kennelly's tables and diagrams of computed and observed magnitudes show the degree of divergence of the "lumpy" artificial line from an equivalent uniform line, but they do not show to what extent the performance of an artificial line may be predicted from predetermined line constants. Mr. Colpitts has, however, thrown some light on this feature. I notice from the figures Mr. Colpitts has given us that there is a close agreement between the empirical constants of the line which are computed back from Dr. Kennelly's experimental results and the actual values given in Table II, except in one very important respect, namely, the apparent resistance. Mr. Colpitts gave the apparent resistance per section computed back from Table VIII as 119 ohms, whereas Dr. Kennelly gives the measured value at 760 cycles, as 33 ohms. Dr. Kennelly points out a large discrepancy between this 33 ohms at 760 cycles and the measured apparent resistance of 125 ohms at 60 cycles, which is closer to the empirical value, 119 ohms, obtained by calculating back, than it is to the measured value of 33 ohms at 760 cycles. This discrepancy is surprisingly large. Can Mr. Colpitts tell how Dr. Kennelly's measurements were derived? Is the capacity the true Maxwellian capacity, that is represented by a 90-degree leading current component, and is the inductance represented by a similar lagging component and the resistance by a pure energy component, or do those constants represent some of the multitudinous methods of measuring capacity, inductance and apparent resistance which do not give the true or Maxwellian values?

E. H. Colpitts: Unfortunately, I can not authoritatively answer Dr. Vreeland's question, because I have not discussed

the point with Dr. Kennelly. I would say, however, that the computations which we have made in order to determine what values of line constants would give the values of surge impedance and propagation constant which Dr. Kennelly found for the line, determined the effective constants at the frequency in question. In the case of the effective resistance, for instance, the value found may correspond to losses in the copper conductor alone or it would correspond to such losses plus losses in an iron core if an iron cored coil had been used. In the same way the capacity and conductance correspond to an ideal condenser, having the value of capacity which I quoted and shunted by an ideal resistance giving a conductance equivalent to the figure quoted.

George A. Campbell (by letter): The paper refers to the fundamental steady state constants of a line as its "surge impedance" and its "hyperbolic angle." Our practise is to call these constants the "iterative impedance" and the "propagation constant" and these terms seem to me preferable because the first is more exact and the other is more fundamental. It is a matter of some importance that the best terminology should be standardized, as these constants occur in almost all discussions of lines, whether uniform, loaded or artificial.

The constant referred to as the "surge impedance" applies to a steady state condition of the line and has no necessary connection with the behavior of the line towards a sudden rush of current. In general, the ratio of the electromotive force to the current is not a constant for an impulse or any other unsteady state, so that the conception of an impedance which has proved so useful in connection with steady state phenomena does not apply to transient phenomena. Heaviside's distortionless circuit is a striking exception, for with that the current which starts out on the line is always an exact copy of the applied electromotive force. If a distortionless circuit were loaded (with the first load not at the sending end) it would have a true surge impedance, which would be the surge impedance of the distorionless circuit taken alone, but its so-called "surge impedance" as that term is used in the paper would be something quite different. As this use of "surge impedance" is a misnomer, it is desirable to adopt a more exact term even if it is not quite as short or familiar.

The term "iterative impedance" is advocated for this constant because the distinguishing feature of the impedance is that it repeats itself if the line is closed through this impedance at the far end. The synonyms such as repeating, periodic, cyclic, were not considered desirable because these terms are in wide use in connection with telephone theory. In mathematics the term is already employed in this same way, the dictionary definitions being:

iterative function: "a function which is the result of successive operations with the same operator." (Century).

"a function resulting from successive operations with the same operator." (Murray).

As applied to a line the "operator" is the transformation due to a section of the line; if the line is uniform the section may be chosen of any length; if the line is of periodic recurrent structure, such as a loaded line or an ordinary artificial line, the minimum section is a periodic interval. The definition which we have adopted is:

Iterative impedance: "the iterative impedance of a line of periodic recurrent structure at a specified point, for propagation in the specified direction, is equal to the limit approached as the line is made infinite in length, by the driving-point impedance of the line beginning at the specified point extending in the specified direction, and terminating in any physically possible impedance."

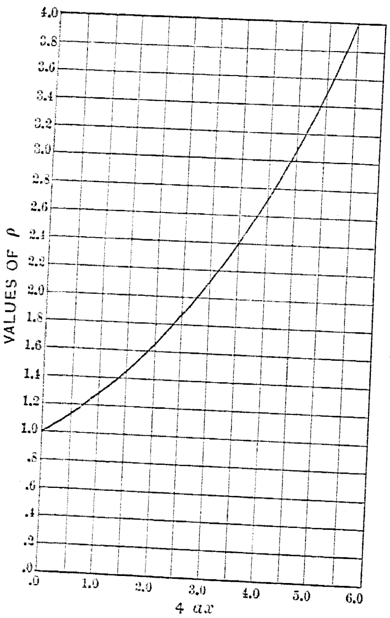


FIG. 1—AMPLITUDE CURVES FOR $e^{x\,(a+i)} = \rho \text{ cis } \theta$

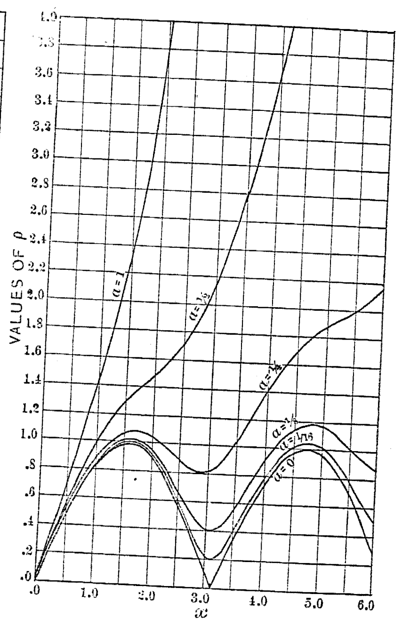


FIG. 2—AMPLITUDE CURVES FOR $\sinh x\,(a+i) = \rho \text{ cis } \theta$

This definition covers uniform lines, loaded lines and artificial lines, which may or may not be symmetrical in the two directions, and it has been made to exclude the theoretical iterative impedance having a negative resistance component by the restriction to any physically possible impedance at the far end of the line.

(Mathematically there are always two iterative impedances for each direction of transmission, one of which has a negative resistance component; the impedances for either direction are equal to the impedances for the other direction with sign reversed.)

"Propagation constant" seems to me to be preferable to "hyperbolic angle" because our basic conception of steady state cisoidal transmission over any periodical recurrent line is that it is compounded of a direct and a reflected wave, each of which falls off exponentially from one periodic interval to the next; we never picture the wave as being divided physically into a hyperbolic sine wave and a hyperbolic cosine wave. In the wave which falls off exponentially, the amplitude decreases in geometrical progression from section to section, while the phase lag increases in arithmetical progression. This is so simple that it is very easily grasped. On the other hand, the

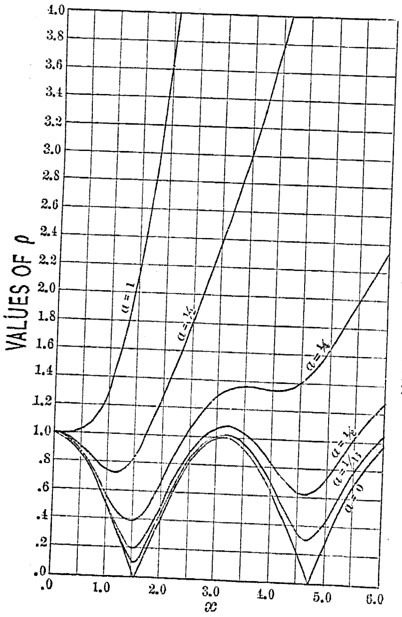


FIG. 3—AMPLITUDE CURVES FOR $\cosh x\,(a+i) = \rho \text{ cis } \theta$

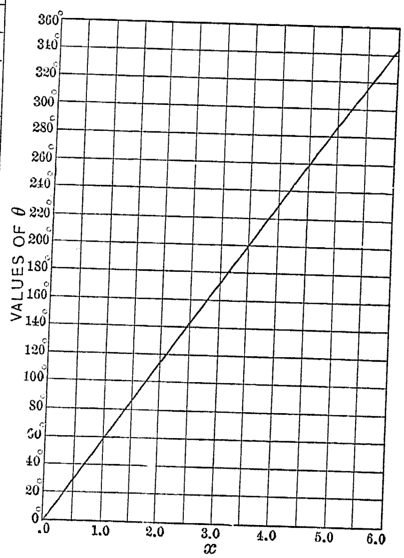


FIG. 4—PHASE ANGLE CURVES FOR $e^{x\,(a+i)} = \rho \text{ cis } \theta$

amplitude and phase relations in a hyperbolic sine or cosine wave are so complicated as to be grasped only with difficulty. The usefulness of hyperbolic functions of complex quantities in transmission theory is mainly confined to analytical work, and it is a matter of comparative indifference whether hyperbolic functions or circular functions of complex quantities are employed, since any expression in one form may be read in the other form without rewriting, and upon clearing the formula of imaginary quantities, hyperbolic functions and circular functions occur in equal numbers.

As hyperbolic functions are analytical means rather than

expressions corresponding to any fundamental physical phenomena, it does not seem advisable to introduce them into the fundamental terminology, while it does seem advisable to retain for the complex quantity which shows how the fundamental exponential wave varies in amplitude and phase the term "propagation constant."

Curves of amplitude and phase angle are shown by the accompanying drawings for cables ($a=1$) and ideal open wire lines ($a=0$) and also for intermediate values of the attenuation constant per wave length. For the exponential function two simple curves suffice for all cases by a mere change in the scales

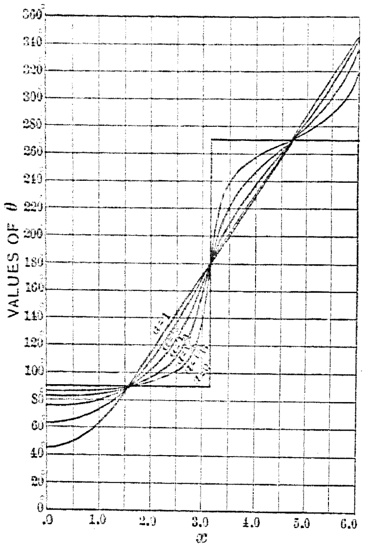


FIG. 5—PHASE ANGLE CURVES FOR $\sinh x\,(a+i)=\rho \text{ cis } \theta$

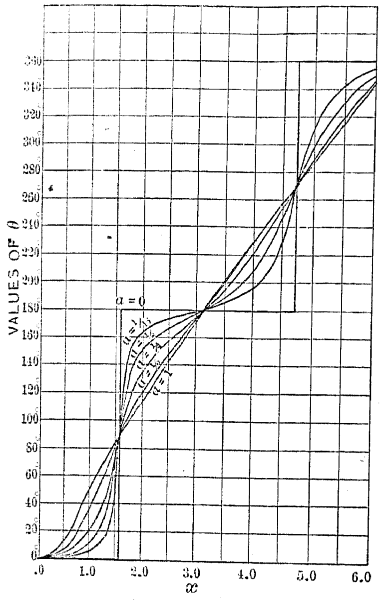


FIG. 6—PHASE ANGLE CURVES FOR $\cosh x\,(a+i)=\rho \text{ cis } \theta$

employed. To picture the hyperbolic function in the same way requires four families of curves which are comparatively complex, the individual curves becoming more and more wavy with decreasing attenuation per wave length.

R. S. Brown: In connection with the curves of current and voltage variation shown in Dr. Kennelly's very interesting paper the author would like to describe a method he has devised for plotting such curves by graphical integration. The method applies equally well to current and voltage on transmission lines, and inasmuch as all the integration is done graphically it is unnecessary to deal with exponential functions. It is

not proposed as a method for solving all transmission line problems, as here length of line is usually a constant and the conditions at some definite point are sought. Such problems are solved more directly by the use of tables of hyperbolic functions, for long lines, and approximations for short lines. This method will prove useful, however, for the solution of lines at high frequency, such as telephone lines, which are not covered by the ordinary tables, and in all cases where it is desired to investigate conditions at progressive points along the line, as in the calculation of corona loss on power lines by the quadratic law.

The well-known differential equations for voltage and current on a line with uniformly distributed constants are:

$$\frac{dE}{dl} = Z\,I \tag{1}$$

$$\frac{dI}{dl} = Y\,E \tag{2}$$

Dividing,

$$\frac{dE}{dI} = \frac{Z}{Y}\frac{I}{E}$$

The integration of this equation gives

$$Y\int_{E_0}^{E} E\;dE = Z\int_{I_0}^{I} I\,d\,I$$

$$Y\,(E^2 - E_0^2) = Z\,(I^2 - I_0^2)$$

or, if $\sqrt{\dfrac{Z}{Y}}$ is the surge impedance of the line, which we will call S,

$$E^2 - S^2\,I^2 = E_0^2 - S^2\,I_0^2$$

Let

$$F = \sqrt{E_0^2 - S^2\,I^2} \tag{3}$$

The quantity F, then, is the same for every point on the line if the line be free from taps.

Solving for I,

$$I = \frac{1}{S}\sqrt{E^2 - F^2}$$

But

$$\frac{Z}{S} = \sqrt{Z\,Y} = \theta$$

where θ is the hyperbolic angle subtended by the line in vector radians per mile.

$$\frac{dE}{dl} = \theta \sqrt{E^2 - F^2} \tag{4}$$

Hence

$$\frac{dE}{\theta\, dl} = \sqrt{(E + F)(E - F)}$$

Since l is a real number it is seen that the angle of $\dfrac{dE}{\theta}$ is one-half the angle of $(E + F)$ plus one-half the angle of $(E - F)$. This angle may be found by bisecting the angle at the vertex

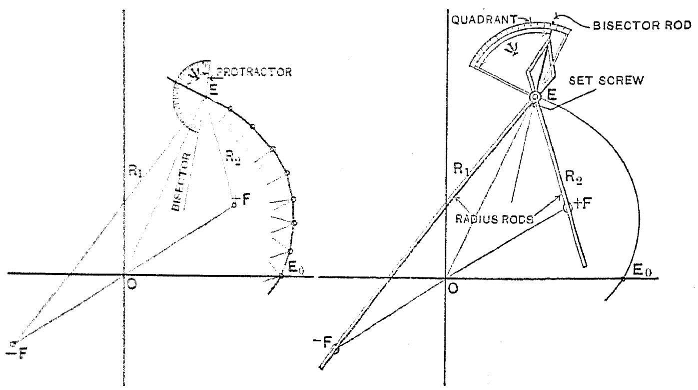


FIG. 1 FIG. 2—PLAN VIEW OF INTEGRAPH.

of the triangle formed with $\pm F$ as base and $(E - F)$ and $(E + F)$ as sides. The angle of dE will then be the angle of θ in advance of the bisector, see Fig. 1. This angle of θ, which we will call φ, depends merely upon the construction constants of the line.

If

$$Z = r + j\,x$$
$$Y = g + j\,b$$

$$\tan \delta = \frac{x}{r} \qquad \tan \epsilon = \frac{b}{g}$$

$$\varphi = \tfrac{1}{2}(\delta + \epsilon)$$

For lines with zero leakage, $g = o$.

$$\varphi = 45^\circ + \tfrac{1}{2}\,\delta$$

Here, then, is a means of plotting the voltage curve. Being the solution of a second order differential equation, it will involve two constants of integration and these are F and E_0. These being laid off on the diagram, the voltage curve may be plotted by drawing a series of connected chords, starting from the point E_0. Each of these chords will be laid off with a protractor φ degrees in advance of the bisector drawn to the point. By a similar construction the current curve may be drawn, except that in this case the constants of integration will be G and I_0, where

$$G = \sqrt{I_0^2 - \frac{E_0^2}{S^2}} \tag{5}$$

From the foregoing it is seen that the current and voltage curves may be defined geometrically as—The locus of a point

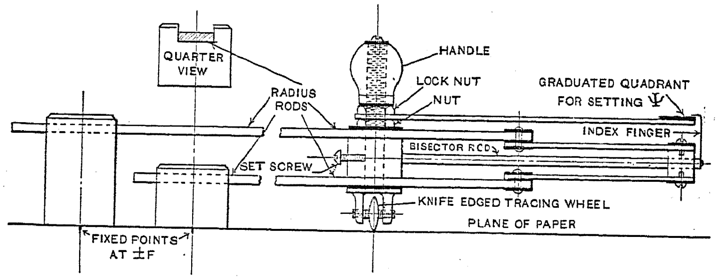


FIG. 3—ELEVATION OF INTEGRAPH

which moves so as to make a constant angle with the bisector of an angle drawn from the point to two fixed points.

Obviously the accuracy of this method will depend upon the shortness of the chords, or, for a given length of chord, upon the radius of curvature. To increase the accuracy the author has constructed an integraph as shown in Figs. 2 and 3. It consists of two steel rods sliding through fixed supports at $\pm F$. The intersection of the rods lies over the point E. Beneath the intersection is a knife-edge tracing wheel which is free to move only in the direction of its plane, being constrained from motion in the direction of its axis by the friction of the knife edge on the paper. By means of a graduated segment and a set screw the plane of the tracing wheel may be set at the angle φ with the bisector of the angle, and it will maintain this angle as it is moved over the paper, tracing out the locus of E. The paths of the wheel may be preserved by placing a piece of carbon paper over the region to be traced. Aside from electrical curves, the instrument may be used to plot any ellipse, or hyperbola, since all these curves obey the above law.

This method would be incomplete without being able to assign to any point on the curve, the lengths of line corresponding. This length is found as follows: The integration of equation (4) gives

$$\theta\, l = \log \frac{E + \sqrt{E^2 - F^2}}{E_0 + \sqrt{E_0^2 - F_2}}$$

Let

$$\frac{E + \sqrt{E^2 - F^2}}{E_0 + \sqrt{E_0^2 - F^2}} = \frac{A\, \sigma^{j\, r}}{A_0\, \sigma^{j\, r_0}}$$

and

$$\theta = (\alpha + j\, \beta)\, l$$

where

α = Attenuation constant

β = Wave length constant.

Then,

$$\alpha\, l + j\, \beta\, l = \log \frac{A}{A_0} + j\, (\gamma - \gamma_0)$$

and

$$\beta\, l = \gamma - \gamma_0$$

It may be shown by analytic geometry, taking F as standard phase, that

$$\cos \gamma = \frac{R_1 - R_2}{2\, F} = \frac{\Delta\, R}{2\, F}$$

R_1, R_2, and F being the scalar values.
Hence

$$\beta\, l = \cos^{-1} \frac{\Delta \mathrm{R}}{2\, F} - \cos^{-1} \frac{\Delta\, R_0}{2\, F}$$

Let the length corresponding to the point E_0 be l_0, then

$$l_0 = \frac{1}{\beta} \cos^{-1} \frac{\Delta\, R_0}{2\, F}$$

and

$$l = \frac{1}{\beta} \left(\cos^{-1} \frac{\Delta R}{2\, F} - l_0 \right)$$

In lines having zero leakage, the wave length constant

$$\beta = \frac{\omega}{\sqrt{2}\, V} \sqrt{1 + \csc \delta}$$

where V is the velocity of wave propagation, approximately that of light. In this case,

$$l = \frac{\sqrt{2}\, V \cos^{-1} \frac{\Delta R}{2\, F}}{\omega \sqrt{1 + csc\, \delta}} - l_0$$

Instead of plotting the current curve, the current corresponding to any point on the voltage curve may be found from the relation

$$S\, I = \sqrt{E^2 - F^2}$$

The magnitude of the current is

$$I = \frac{\sqrt{R_1\, R_2}}{S}$$

R_1, R_2, and S being the scalar values.

The angle between current and voltage is the angle between the bisector and the median of the triangle, plus $\frac{1}{2}$ $(\delta - \epsilon)$ degrees.

It is interesting to note the limiting forms taken by the current and voltage curves under extreme conditions.

1. When the frequency becomes very high the reactive constants, x and b, become large compared with the constants r and g which dissipate energy, and the locus approaches a closed curve—an ellipse with $\pm\, F$ as foci, $\varphi = 90$ deg.

2. When the frequency becomes very low the dissipative constants, r and g, predominate, and the locus approaches a hyperbola with $\pm\, F$ as foci, $\varphi = 0$.

3. When $I_0 = 0$ (no load) the locus of E becomes the graph of cosh $\theta\, l$.

4. When $E_0 = 0$ (short circuit) the locus of E becomes the graph of sinh $\theta\, l$.

5. When the line approaches infinite length the distorting factor, F, due to the reflected wave, disappears and the locus becomes a logarithmic spiral. This factor also disappears when the impedance of the load is equal to the surge impedance of the line, in which case the generator wave is entirely absorbed by the load and no reflection ensues.

6. When the conditions mentioned in 5 obtain and the reactive constants predominate, the locus approaches a circle.

The distortion noticed in Dr. Kennelly's curves for the first wave length or so is due to the reflected wave. As a greater distance from the open end is attained, the reflected wave becomes damped out and all the curves approach logarithmic spirals.

J. B. Taylor: While abstracting his paper, Mr. Friendly remarked that while a technical engineer might be disposed to object to some of the automatic devices described, the commercial engineer would be satisfied that the use of the additional devices and complications had justified itself.

While I have no reason to assume that the particular arrangements described in this paper may be in any way detrimental to the service, I wish to remark that, in general, there is some risk in going so far with automatic devices that the actual telephone service (*i.e.*, the transmission of speech from one subscriber to another, neither of whom is interested in the modes of operation of the devices by which the communication is established) is impaired.

To illustrate this point, mention need only be made of the undesirable and frequently painful, if not dangerous, noises to which we are subjected when using telephones connected to certain common battery systems. The original magneto systems, while undesirable in many respects, were less noisy.

H. M. Friendly: In reply to Mr. Taylor's remarks, if you will look over the circuits carefully you will find that nothing has been introduced in the circuits of the equipment which will attenuate speech appreciably, such as is the case in some types of telegraph equipments applied to telephone lines.

In regard to the noises referred to, we have made a particular effort to avoid extraneous noises of every kind; and in the latter part of the paper our views will be found on that phase. I agree with Mr. Taylor very thoroughly in that extraneous noises on a telephone line, the humming and clicking, are very detrimental to service. The conversers will invariably pause after a clicking sound and then shout at each other to ascertain if they have been cut off, and it is sometimes a large fraction of a minute before they get under way again after the disturbance has ceased. In all the apparatus designed we made it a first consideration to eliminate disturbances.

Oberlin Smith: It seems to me that any advance toward automatic service should be welcomed and should be developed and discussed. We all know there are tremendous difficulties in telephone exchange work of any kind, sometimes even in pleasing subscribers.

Taking an optimistic view, I do not think there is any question but what in the sometime golden future, I will not say when, all telephony will be automatic, and we will talk all over the world by merely arranging our own instrument, with its buttons or levers, or what not, for the connection desired. We should welcome all improvements in this line as steps towards the ultimate automatic telephony which may extend its arms all over a continent, if not indeed to the ends of the world.

H. M. Friendly: In regard to the reliability of the apparatus, we have not found the apparatus to give serious maintenance trouble at all. The switch sets look complicated on paper, though in a period of some months' test no adjustments were made in any manner to the connecting switch of the through switch switching set, though changes were made in circuit details on several occasions in the development of the apparatus.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

ELECTROLYTIC CORROSION OF IRON IN SOILS

BY BURTON MCCOLLUM AND K. H. LOGAN

The term electrolytic corrosion is most frequently used to indicate corrosion caused by the discharge of an electric current which enters the metal from external sources. During recent years, however, the theory has been widely accepted that all corrosion in water solutions is essentially electrolytic in its nature, and in consequence there have come into use a variety of terms such as "galvanic action," "stray current electrolysis," "self-corrosion," etc., to distinguish between the cases of corrosion originating from different causes. Thus corrosion of buried iron may be due to galvanic action caused by physical or chemical differences between adjacent points on the surface of the metal, to the presence of foreign substances in the soil such as coke, cinders, iron oxides, etc., which set up local galvanic action, or it may be due to the discharge of electric currents that have entered the structure at some remote point. In the present paper the terms "electrolysis" and "electrolytic corrosion" are used to designate corrosion caused by the discharge of electric current which has entered the metal from some outside source, while all other forms of corrosion in which the electric currents originate within the corroding system itself from whatever cause, are referred to as "self-corrosion." It should be pointed out at the outset, however, that these two general classes of corrosion are by no means independent of each other, since the presence of either kind of corrosion generally affects in marked degree the nature and extent of the other, under a given set of conditions. This mutual influence is such as to be of considerable practical importance, and in particular it often greatly increases the difficulty of obtaining

trustworthy experimental data in regard to electrolytic corrosion proper.

The data herein presented represent a portion of the work done by the Bureau of Standards in connection with a more general investigation of the subject of electrolysis and electrolysis mitigation, which has been in progress for some time past. The present paper is designed to deal only with the fundamental laws governing electrolytic corrosion under practical conditions, and relates to self-corrosion only in so far as it is necessary to distinguish between the two classes. The subject of the prevention of electrolytic damage is referred to only incidentally when occasion requires in order to interpret the significance of results obtained. This matter of electrolysis has been given much attention, but is far too comprehensive a subject to be dealt with in a brief paper such as can be presented here. It will be treated at some length, however, in a report which will be issued shortly by the Bureau of Standards, dealing exclusively with the subject of electrolysis mitigation.

In studying the phenomena of electrolytic corrosion in soils under practical conditions, many variables are encountered which tend in greater or less degree to affect the results. Among these may be mentioned the current density at the surface of the metal, the moisture content of the soil, and the presence of oxygen either in the gaseous state or dissolved in soil waters. The latter not only affects the rate of corrosion but also affects the character of the end products of the reactions and thus to some extent has a bearing on the question of diagnosing the cause of particular cases of corrosion. The temperature of the soil is also important, particularly because of its effect on the current flow. In the case of iron, the formation of oxides as a result of the initial corrosion may complicate matters because of their possible effect in stimulating galvanic action. Other factors, such as the mechanical and chemical properties of the soil, the depth of burial of the metal, the limitation of current flow due to polarization, the formation of high-resistance films on the surface of the metal, and the pitting of the surface due to a variety of causes, may likewise act to increase or decrease the rate at which damage may progress, and therefore require special investigation. Finally, since it is not practicable to carry on all experiments in the field under practical conditions, it is necessary to study the possible differences in results that may in some cases occur between experiments performed in

the laboratory and in the field. It is these factors that are dealt with in the following pages, and while the investigations have in most cases not yet been completed, we believe that the data thus far obtained will be of sufficient interest to justify a report of progress at this time.

While the corrosion of iron by electric currents may be influenced by a variety of causes, nevertheless the data to be presented later show that under most practical conditions the extent of the corrosion is largely a function of the quantity of electricity that is discharged from a given surface. This is a quantity that can be readily measured under laboratory conditions and we have therefore determined, in all cases, the corrosion as a function of the ampere-hour discharge from the anode. The results are expressed in terms of the "corrosion efficiency." If the corrosion of the anode is the sole action involved at the anode, then, according to Faraday's law, 96,540 coulombs are required to corrode one gram-equivalent of the metal, and the corrosion efficiency is said to be 100 per cent. In most cases, however, the actual corrosion noted is either greater or less than this amount, and the percentage which the actual corrosion, in any case, is of the theoretical amount, is called the "efficiency of corrosion" under those conditions. The experimental data presented in the first part of this paper show how the efficiency of corrosion is affected by the varying physical conditions encountered in practise. The corrosion efficiencies are in all cases calculated on the assumption that the iron is divalent. The experiments presented show that in most cases, at least, this is true, since, as a rule, the corrosion efficiencies observed have been near or above one hundred per cent. This is therefore the logical basis on which to figure the efficiency of corrosion. In those cases where the corrosion efficiency was very low it may have been due in part to the iron taking the ferric state, and such tendency, when it exists, may therefore be regarded as one of a number of possible causes of low efficiency of corrosion. The various factors enumerated above which affect the efficiency of corrosion of iron in soils, are discussed in detail in a later part of this paper.

Arrangement of Apparatus

The methods of conducting the experiments recorded below were in general the same, and may, therefore, be described once for all.

The local earths used in the laboratory tests were from virgin soil near the laboratory, sifted to remove stones and to insure uniformity. This earth was mixed with the desired amount of distilled water and placed in tin cans which served as cathodes. The bottoms of the cans were separated from the earth by a thick layer of paraffin or other insulating material so that the discharge from the anode placed in the center of the can would be substantially uniform and only toward the sides of the can. The outsides of the cans were insulated from each other by several layers of heavy paraffined paper. In a number of experiments, however, the test specimens were buried in virgin soil out of doors in order to compare directly the corrosion found under these conditions with the corrosion which resulted when the tests were made in the laboratory.

Cleaning of Anodes

In cleaning the anodes and determining their losses, a number of precautions are necessary. It has been shown that many solutions render iron at least temporarily passive. Such solutions are, of course, not desirable for cleaning iron previous to a test. The iron used was filed and sandpapered to remove dirt and scale, cut into suitable lengths, stamped on one end for identification with steel numbers, and weighed. Rubber-covered leads were then soldered to the unnumbered ends of the anodes and both ends covered with paraffin or pitch. To make these stick to the iron it is necessary that it should be rather hot when they are applied. The specimens were then thoroughly washed with gasoline to remove any grease due to handling and finally dried with a towel. At the close of the experiment the specimens were washed and brushed to remove all loose dirt and then made cathode in a two per cent solution of sulphuric acid with a high current density. To prevent plating a non-corrodable anode should be used. This method of cleaning was developed after various mechanical and chemical methods had been tried with inconsistent results, and has proved very satisfactory. The specimens came from the solution perfectly clean within ten to thirty minutes and careful tests have shown that clean iron subjected to the treatment suffers no loss.* The method seems very much preferable to any mechanical method we have tried, because, when the rust sticks very tightly or the iron is rough, it is impossible to remove the

*This does not apply to cast iron.

corrosion products without scraping off some of the iron with them. In a few instances where it was not convenient to clean the iron electrolytically, as in the case of hollow anodes too small to permit the interior to be protected by inserting an anode, a solution of ammonium citrate has been used. This latter method is satisfactory except in the case of deep pits, especially if a warm solution is used.

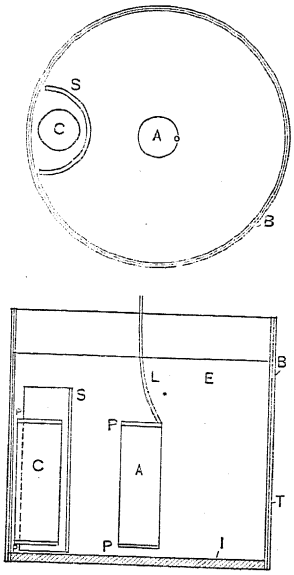


FIG. 1—ARRANGEMENT OF ANODE AND CHECK SPECIMEN

A—Anode $1\frac{1}{2}$ in. diam.; B—paraffined paper, 2 layers; C—check specimen $1\frac{1}{2}$ in. by $\frac{1}{2}$in. diam.; E—earth; I—paraffine $\frac{1}{8}$ in.; L—lead No. 18 rubber covered; P—pitch layer; S—glass shield one inch diam.; T—tin can 3 in. diam., $3\frac{1}{8}$ in. high.

The paraffin protecting the ends of the specimens was removed by gasoline and the pitch by toluol. The solder attaching the leads was melted and carefully wiped off. We have also tried dissolving the solder by mercury but the process is slow unless heat is used, and the result no better than the easier method.

CHECK SPECIMENS

Correction for the loss by the anodes due to self-corrosion was made by placing a check specimen inside each can and screening it from the anode by a shield of glass or paraffined paper. Fig. 1 shows the arrangement of the anode and check specimen. The loss of the check specimen has been deducted from the loss of the anode and the difference used as the loss due to electrolysis. It will be shown later that the loss of a check specimen in a can with an anode is considerably greater than that of a similar check specimen in a separate vessel of the same earth and it seems therefore that part of the loss in the former case is due to some effect of the current and should be against it. The corrosion efficiencies found are therefore charged lower than if check specimens in separate cans were used. However, there are several advantages in keeping the check specimen in the can with the anode, and the increased loss on this account is usually small, compared with the total loss of the anode.

Determination of Ampere-Hours

To obtain the corrosion efficiency it is, of course, necessary not only to determine accurately the loss of the anode, but equally essential to know the quantity of electricity discharged by it. To obtain this, the specimens were so arranged that the currents could be read at frequent intervals, compensation being provided where necessary for the resistance of the milliammeter. Curves were plotted showing the relation between current and time, and the area between the curve and the axes determined with a planimeter. While the exact current values between times of observation are unknown, the areas represent a value of the ampere-hours sufficiently accurate for practical purposes, and the large number of circuits operating at one time made the use of more accurate recording instruments out of the question.

I. Factors Affecting Efficiency of Corrosion

1. *Effect of Current Density.* A number of investigators have reported experiments showing that the amount of corrosion which results from a given ampere-hour discharge varies greatly from the theoretical amount. Among these may be mentioned the work of Hayden[1] and of W. W. Haldane Gee [2] who worked with high current densities, and observed that there was a marked tendency for the iron to become passive, the resulting corrosion being considerably less than the theoretical amount. In general, this tendency toward passivity was much more marked when the current density was made very high. These experiments were carried out with test specimens immersed in liquid baths, however, so that the conditions were very different from those which prevail in ordinary street soils. Ganz[3] has reported the results of experiments carried out in certain soils, which showed that the actual corrosion observed was much greater than the theoretical amount, in some cases the loss in weight being as much as several times the loss calculated from Faraday's law. In these experiments very low current densities were used and the earth contained considerable quantities of salt and this may have affected the result. The authors have carried out several series of experiments in which the aim

1. *Journal of the Franklin Institute*, Vol. CLXXII, p. 295.
2. *Journal of the Municipal School of Technology*, Manchester, Vol. 2, 1910.
3. Trans. A. I. E. E., 1912, Vol. XXXI, p. 1167.

has been to maintain conditions as nearly as possible approximating those which will be encountered in practise, both as regards soil conditions, and current densities. The soil used was a virgin soil taken from a sparsely settled portion of the residential district of Washington. An analysis was made of a typical sample of the soil for those ingredients which are most likely to affect corrosion, the results being shown at the top of Table I along with the data on efficiency of corrosion. In determining the current densities to be used, values were chosen of such magnitude as could give rise to considerable injury within a period varying from a few months to fifteen or twenty years. For example, the highest value used was about 5 milliamperes per square centimeter, which under uniform distribution and at 100 per cent efficiency of corrosion would cause the corrosion to progress inward at the rate of about 5.7 centimeters per year, which corresponds to a rate rarely exceeded under practical conditions. The minimum current density used was 0.05 milliamperes per square centimeter, which corresponds to a normal rate of corrosion of about one centimeter in 17 years. These extreme ranges represent, therefore, the limits between which the corrosion is of much practical importance.

Several series of experiments were made, the data presented in Tables I and IA being typical of the series. The corrosion efficiencies under Table I are for a soil containing considerably less moisture than those under Table IA, which were obtained in a soil practically saturated with water. In the former the test specimens were all imbedded in samples of earth placed in tin cans as described above, while in the second series half of the tests were run with specimens buried to a depth of about 2½ ft. (76 cm.) in the ground out of doors.

The data in Table I are plotted in Fig. 2, and those of Table IA are plotted in Figs. 3 and 4, the curve of Fig. 4 being a continuation of that of Fig. 3, but on a smaller scale. While the points do not lie on a smooth curve, because of a number of disturbing factors to be discussed later, the trend of the curves is nevertheless unmistakable. They show corrosion efficiencies varying greatly with the current density, the ranges being from about 20 to 140 per cent for the range of current density varying from about 5 to 0.05 milliamperes per square centimeter, the lower corrosion efficiencies being obtained at the higher current densities. All of the data in Tables I and IA are plotted as a single curve in Fig. 5, which, in spite of

TABLE I

RELATION BETWEEN CURRENT DENSITY AND EFFICIENCY OF CORROSION

PARTIAL ANALYSIS OF SOIL USED IN TESTS

Cl_1	NO_3	CO_3	SO_4
0.002%	0.002%	0.003%	0.004%

No.	Current Density milliamps. per sq. cm.	Efficiency of corrosion
1	2.0	57.6
2	1.8	37.4
3	1.7	69.2
4	1.6	43.2
5	1.5	84.3
6	1.3	75.8
7	1.2	72.8
8	1.1	83.8
9	1.0	89.2
10	0.8	75.0
11	0.7	88.3
12	0.6	79.1
13	0.5	75.2
14	0.4	102.1
15	0.3	142.2
16	0.2	96.2
17	0.1	148.4
18	0.05	142.9

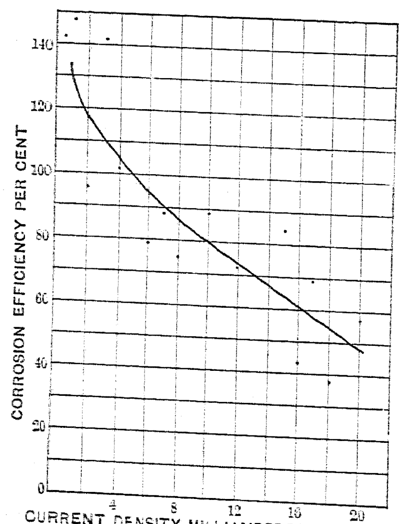


FIG. 2—CORROSION EFFICIENCY—CURRENT DENSITY

the irregularities in the individual points, shows clearly the decided falling off in efficiency of corrosion with increase in current density. It is interesting to note here that the points in Fig. 5 marked with an X were taken out of doors in native earth while those marked with dots and circles were two separate

TABLE IA

CURRENT DENSITY-CORROSION EFFICIENCY

AREA OF ANODES, 70.9 SQ. CM. TIME OF RUN, 115 HOURS

No.	Current density milli-amps. per sq. cm.	Corrosion efficiency
19	0.034	124.1
20	0.064	115.0
21	0.088	141.5
22	0.129	123.6
23	0.150	104.6
24	0.163	118.3
25	0.206	125.8
26	0.222	117.1
27	0.258	101.8
28	0.279	113.4

CURRENT DENSITY-CORROSION EFFICIENCY

72-HOUR RUN IN SATURATED SOIL IN LABORATORY. 4-27-13 TO 4-30-13. EXPOSED ANODE AREA, 11.78 SQ. CM.

No.	Current density Milliamps. per sq. cm.	Corrosion efficiency
29	0.48	102.5
30	1.01	98.1
31	1.26	78.3
32	1.84	102.2
33	2.28	63.6
34	2.50	78.1
35	3.45	52.9
36	4.27	43.6
37	4.29	27.4
38	4.72	20.4

series taken indoors, using small samples of earth in cans. The agreement between the different groups is fully as good as that between different points of the same group, which indicates that the results obtained on small samples in the laboratory are substantially the same as those obtained on specimens

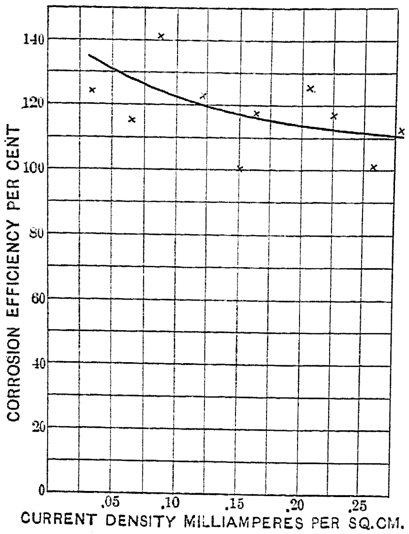


FIG. 3—CORROSION EFFICIENCY—CURRENT DENSITY

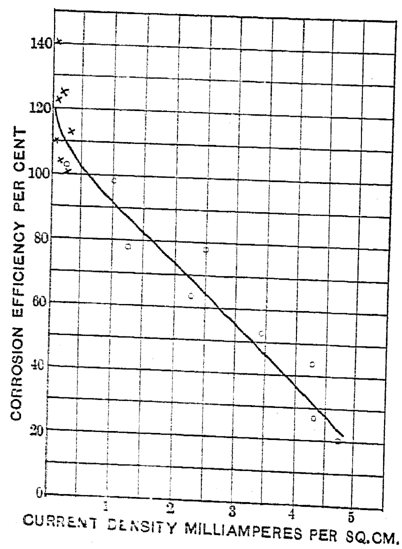


FIG. 4—CORROSION EFFICIENCY—CURRENT DENSITY

buried in the earth out of doors. This gradual change in corrosion efficiency with current density does not appear in accord with the results of Hayden, Haldane Gee, and others, whose work with liquid electrolytes seemed to indicate an abrupt change in efficiency of corrosion from 100 per cent to zero at a critical current density.

It will be noted that these results do not show as high efficiencies of corrosion as those reported by Prof. Ganz[4], who found values ranging over 500 per cent. It should be noted, however, that the results obtained by Prof. Ganz were for the most part obtained on much lower current densities than were used in the present experiments. It is seen also from Fig. 5 that as the lower current densities are approached the curve tends rather strongly upward, indicating that if the current density

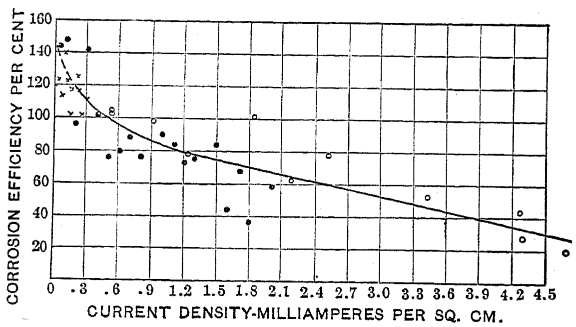


FIG. 5—CORROSION—CURRENT DENSITY

had been reduced to the low value used by Ganz, the corrosion efficiencies might have reached the high values found by him. As pointed out above, however, lower current densities than those used in the present series, although of great theoretical interest, are of little consequence from the practical standpoint.

2. *Effect of Moisture on the Rate of Corrosion.* The following experiment was tried to determine whether the amount of moisture in the soil affected the corrosion efficiency of iron buried in it:

A quantity of red clay soil was air-dried and then distilled water was added, a can of earth taken out; more water added, etc., till twelve cans of earth had been obtained.

The ends of the specimens and the bottoms and outsides of the cans were insulated as in previous tests, and small dishes

4. TRANS. A. I. E. E., 1912, Vol. XXXI., p. 1167.

of water placed inside the cans to retard evaporation. The six cans were connected in series, the sides of the cans serving as cathodes, and a current of two milliamperes giving about one milliampere per square centimeter, was maintained by daily adjustments for 86 days. At the end of this time the resistance had increased so much that it was difficult to maintain the current and the specimens were therefore removed, cleaned and weighed. The efficiency of corrosion was then computed, corrections being made for self-corrosion.

While the current was flowing, samples of the earth, taken when the specimens were placed in the cans, were dried for about a week in an oven at a temperature of 105 deg. cent. and the percentage of moisture computed from the loss of weight. The

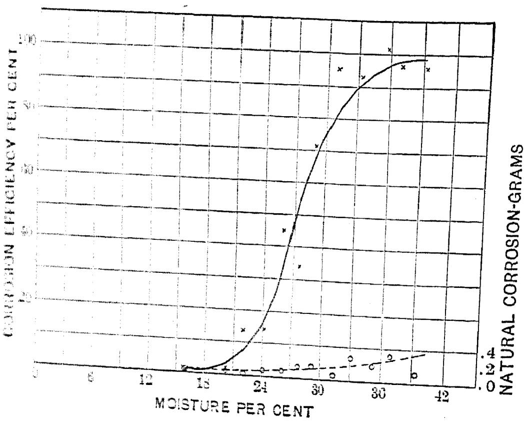


FIG. 6—CORROSION EFFICIENCY MOISTURE
Natural corrosion moisture

per cent of moisture is expressed in terms of the earth before drying.

The result of this test is given in Table II, and plotted in Fig. 6.

Looking at the curves of self and electrolytic corrosion, it will be seen that where a point on one curve is too high, the corresponding point on the other curve is too low. Since the electrolytic curve was obtained after natural losses had been deducted it is evident that part of the irregularities is due to incorrect values of the natural loss. However, the natural loss is so small that in most cases it could not account for the entire variation in the electrolytic curve. Since all wrought iron contains more or less slag it is probable that the presence

of minute slag particles explains, in part at least, the pitting and variations of results from expected values.

The results of these tests show that the corrosion efficiency varies greatly with the moisture content of the soil, being so small as to be practically negligible when the soil is fairly dry, but approaching values of the order of 100 per cent when the soil becomes saturated. In these tests there was very little corrosion when the moisture content was below 20 per cent. It should not be assumed, however, that the numerical values given here will hold for all soils, since there is considerable uncertainty as to the conditions which actually prevail.

In the first place, the percentage of moisture required to produce a wet condition of the soil varies greatly with different

TABLE II
EFFECT OF MOISTURE ON CORROSION

No.	Per cent moisture	Loss—grams			Per cent efficiency
		Total	Natural	Electrical	corrosion
1	15.9	0.090	0.044	0.046	1.1
2	20.0	0.110	0.040	0.070	1.6
3	22.5	0.623	0.039	0.584	13.7
4	23.8	0.715	0.080	0.635	14.9
5	26.0	2.002	0.073	1.929	45.3
6	27.6	1.579	0.145	1.434	33.7
7	28.9	3.192	0.160	3.032	71.2
8	31.1	4.182	0.121	4.061	95.4
9	33.3	4.217	0.265	3.952	92.8
10	35.7	4.545	0.207	4.338	101.9
11	37.0	4.463	0.335	4.132	97.0
12	39.4	4.218	0.125	4.093	96.2

soils, so that the percentage of moisture cannot be taken as a measure of the condition of dryness. In the red clay soil used in these tests the soil appeared to be barely moist at 15 or 20 per cent moisture; whereas in many cases we have since encountered numerous soils in which 10 per cent of moisture caused it to appear quite wet. There may also be variations due to differences in soil composition which affect the efficiency of corrosion. Further, while the average current density in these experiments was maintained practically constant, it is not improbable that the actual current density varied considerably. When the soil was practically saturated with water the current density would probably be nearly uniform, but as the moisture content is reduced and some of the pores in the soil became voids,

there would be a tendency for the current to discharge locally at the points of contact between earth and iron, and it appears possible that this might give rise to great variation in the actual current density of the discharge. It has already been seen that at high current densities the efficiencies of corrosion tend to become smaller, so that the variations in efficiency of corrosion here observed as due to changes in moisture content, may after all be due in large part to changes in current density. However this may be, the important fact is that the amount of corrosion per ampere-hour is likely to be quite low in the case of fairly, dry soils whereas, as the percentage of moisture approaches that corresponding to saturation, the corrosion efficiency approaches 100 per cent for the particular value of current density used in this series, namely, one milliampere per square centimeter.

3. *Effects of Temperature.* In order to study the effects of temperature on the efficiency of corrosion of iron in soil, three series of experiments were carried out. In the first of these, the temperature of the cans containing the earth samples was maintained practically constant at between zero and one deg. cent. by means of an ice bath; the second was run at between 24 and 27 deg. cent., which corresponds to about average summer temperature in soils, and the third group was maintained at between 35 and 40 deg. cent. by means of an automatically regulated oven. Four specimens were used in each group, and the current density was maintained practically constant at about 0.84 milliamperes per square centimeter.

The tests were all run in the same kind of earth, which was kept practically saturated with moisture. The results of these tests are given in Table III. An examination of the values of efficiency of corrosion will show that they are practically independent of the temperature. It appears, therefore, that it is safe to assume that throughout the range of temperatures that is likely to be encountered under practical conditions, temperature variations have no marked effect on the corrosion efficiency of iron in soils. This does not mean, however, that temperature is not an important factor in electrolysis under practical conditions, for the reverse is true; but this grows out of the effect of temperature on the resistance of the soil rather than on the efficiency of corrosion. It is shown in a later part of this paper that the resistance of soils varies with temperature in a very remarkable manner, even within the ranges of temperature that

are likely to occur in soils under ordinary conditions, and that the effect of this change in resistance on the current flow is such as to make the actual amount of electrolysis which may be expected, vary greatly with temperature. This matter is discussed later under the head of earth resistance.

4. *Effect of Depth of Burial on Efficiency of Corrosion.* Inasmuch as the efficiency of corrosion is found to vary greatly under different conditions, it was deemed advisable to investigate whether the depth to which a pipe is buried below the surface would have any effect on the efficiency of corrosion. Accordingly a number of specimens were prepared and buried in earth

TABLE III

EFFECT OF TEMPERATURE ON CORROSION EFFICIENCY

No.	Temperature	Corrosion efficiency
	deg. cent.	
1		98.2
2	35 to 40	103.4
3		97.0
4		98.4
	Average	99.2
5	24 to 27	98.2
6		97.6
7		97.9
8		97.6
	Average	97.8
9		93.8
10	0 to 1	95.7
11		99.1
	Average	96.2

Average current density 0.84 milliamperes per sq. cm.

to distances varying from a few inches to about six feet. A check specimen was provided in each case to permit correction for self-corrosion, and it was so shielded as to prevent the passage of any current through it. The anodes and check specimens alternated with each other in the order given in Table IV. In correcting for self-corrosion the mean of the losses on the check specimens on both sides of each anode was used. The specimens were buried in virgin red clay soil and were run at an average current density of about 0.056 milliamperes per sq. cm. for about 1490 hours. The results of the tests are shown in Table IV and plotted in Fig. 7, which gives curves of both self-corrosion and efficiency of corrosion as a function of depth. It wil

be seen that the results, while somewhat irregular, indicate that there is but slight variation attributable to depth, although there seems to be a trend upward in the case of self-corrosion. The variation in efficiency of corrosion with depth is probably due to the fact that the moisture content varied with depth. The fact that no greater variation was observed is doubtless due to the fact that the tests were carried out at a time when the soil was fairly wet, both near the surface and at greater depths. The results given above on the effect of moisture content indicate that if the experiments had been made in a fairly dry time when there was considerable variation of moisture content with depth, the corrosion efficiency would probably have shown a

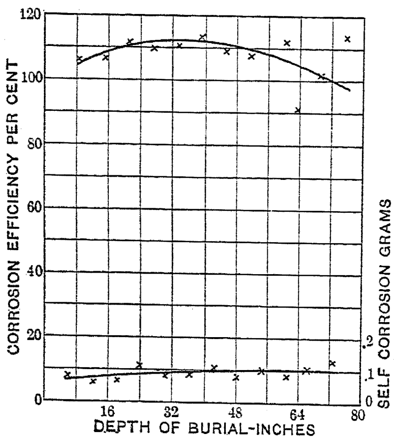


FIG. 7—CORROSION EFFICIENCY—DEPTH

corresponding variation. When conditions are such that there are considerable variations in moisture content with depth, as in a moderately dry time for instance, the preceding data indicate that the efficiency of corrosion would probably also vary greatly with depth, being in general, greater the greater the depth.

5. *Effects of Oxygen on Corrosion of Iron.* Since, according to the electrolytic theory of corrosion, the presence of oxygen is an essential factor in the production of self-corrosion of iron in the presence of water, it might be expected that the electrolytic corrosion of iron by stray currents would be affected in a marked degree by the content of dissolved oxygen in soil water. In order to investigate this point, ten anodes and a corresponding number of check specimens having an exposed area of 90 sq.

cm. each were prepared in the usual way and connected in series and run on a practically constant current density of 0.056 milliamperes per square centimeter. Five of these jars were so arranged that oxygen bubbled through the liquid continuously throughout the entire experiment, and the other five were immersed in the water without oxygen being

TABLE IV

EFFECT OF DEPTH OF BURIAL ON NATURAL AND ELECTROLYTIC CORROSION

WROUGHT IRON CYLINDERS 2 IN. (5.08 CM.) LONG AND 1⅜ IN. (3.4 CM.) IN DIAMETER, POLISHED. ODD NUMBERS CARRIED CURRENT. EVEN NUMBERS ARE FOR NATURAL CORROSION

No.	Total loss	Electrical loss	Loss theoretical	Per cent efficiency	Depth Inches
1	9.260 g.	7.972 g.	6.990 g.	114	75
2	1.288				72
3	9.475	8.319	8.119	102	69
4	1.024				66
5	7.630	5.685	6.280	91	63
6	0.875				60
7	10.862	9.929	8.785	113	57
8	0.991				54
9	9.422	8.512	7.890	108	51
10	0.829				48
11	8.505	7.593	6.959	109	45
12	0.995				42
13	8.822	7.866	6.942	113	39
14	0.916				36
15	8.225	7.341	6.618	111	33
16	0.852				30
17	6.899	5.913	5.385	110	27
18	1.120				24
19	7.331	6.424	5.780	111	21
20	0.694				18
21	4.667	3.993	3.732	107	15
22	0.654				12
23	5.092	4.420	4.226	105	9
24	0.690				6

Area of surface 70.9 sq. cm.
Mean current density about 0.059 milliamperes per sq. cm.

passed through them. At the end of 183 hours the experiment was completed and the anodes were weighed and efficiencies of corrosion calculated. The data are given in Table V, from which it will be seen that there is considerable variation in the efficiencies of corrosion for the individual specimens. These variations are so large that the difference between the average of the five specimens in the jars through which oxygen was

passed (98.5 per cent), and the average for those specimens in the remaining jars (91 per cent), has but little significance. It is, of course, necessary to bear in mind in interpreting these results that even the water through which oxygen was not passed, contained a good deal of oxygen in solution, so that any differences in efficiency of corrosion that might be indicated would be those due to a somewhat indefinite difference in the oxygen contained in the water.

TABLE V

EFFECT OF OXYGEN ON EFFICIENCY OF CORROSION

CURRENT DENSITY 0.056 MILLIAMPERES PER SQ. CM. TIME 183 HR. AREA OF ANODES 90 SQ. CM.

A—OXYGEN ADDED

No.	Total loss	Self-corrosion	Electrical loss	Per cent efficiency of corrosion
0	1.248g.	0.182g.	1.066g.	110.7
1	1.251	0.312	0.939	97.5
2	1.296	0.330	0.966	100.5
3[1]	0.993	0.067	0.929	96.5
4	1.128	0.327	0.801	87.0
			Average	98.5

B—NO OXYGEN ADDED

No.	Total loss	Self-corrosion	Electrical loss	Per cent efficiency of corrosion
5[1]	0.886	0.030	0.873	90.6
6	0.940	0.027	0.913	94.9
7	0.913	0.029	0.884	91.7
8	0.889	0.030	0.859	89.0
9	0.895	0.040	0.855	88.7
			Average	91.0

1. Buried in sand.

In order to check this result more carefully, two series of experiments were carried out in which a much larger difference in the oxygen content in the two cases was maintained. In each series four specimens were used, two being placed in tap water and the other two in a 10 per cent solution of sodium sulphate. In one series the liquids were first boiled down to half their original volume in Erlenmeyer flasks to remove oxygen, and the iron electrodes inserted during boiling. After the boiling, an atmosphere of hydrogen was introduced into

the flasks as they cooled down, so that practically no oxygen could have access to the liquid. In the other series air was caused to bubble through the liquid throughout the experiment so that an abundant supply of oxygen was always present. The results are given in Table VA. From this table it will be seen that there is no appreciable difference between the efficiencies of corrosion in the presence of oxygen and in the absence of oxygen, at least in the liquid electrolytes here used. We have reason to believe, however, that this is not the case when the anodes are buried in soils, although just why a difference should

TABLE VA

EFFECT OF OXYGEN ON EFFICIENCY OF CORROSION

WEIGHTS

No.	Solution	Original	Final	Loss	Per cent corrosion efficiency
		WITHOUT OXYGEN			
1	H_2O	51.326g.	50.624g.	0.702g.	96.2
2	H_2O	51.570	50.871	0.699	95.8
3	10% Na_2SO_4	52.361	51.651	0.710	97.3
4	10% Na_2SO_4	51.642	50.935	0.707	96.9
				Average	96.5
		WITH OXYGEN			
5	H_2O	51.852	51.154	0.698	95.7
6	H_2O	52.725	52.044	0.681	94.7
7	10% Na_2SO_4	51.467	50.759	0.708	97.0
8	10% Na_2SO_4	51.034	50.317	0.717	98.2
				Average	96.4

Theoretical loss, 0.730 g.
Area of anodes, 15.2 sq. cm.
Current density, 1.45 milliamperes per sq. cm.

exist here is not clear. That there is a difference is borne out by a number of tests we have made with anodes buried in earth in hermetically sealed cans and others buried in cans exposed to the atmosphere, conditions as to moisture content, current density, etc., remaining the same. Whenever the tests were continued for a considerable time it was found that the efficiency of corrosion in the sealed receptacle was in nearly all cases considerably lower than when the container remained open. This effect is shown in Table VI.

The average corrosion efficiency in the closed cans was 85.5 per cent while that in the open cans was 105.7 per cent.

Whether or not this difference is due to the difference in the amount of oxygen or CO_2 present or to other causes, it affords another indication of the danger of drawing conclusions from experiments made in liquid electrolytes as to what would occur in the case of electrodes buried in soils.

6. *Effect of Oxygen on the End Products of Corrosion.* One very marked effect of oxygen on corrosion, however, is its influence on the final products of electrolysis. There is a very common impression extant that the final products of corrosion of iron due to stray currents are the black oxides, whereas in the case of self-corrosion red oxides are produced. This is not in

TABLE VI

CORROSION EFFICIENCIES IN OPEN AND CLOSED CANS

No.	Efficiency of corrosion	
	Closed cans	Open cans
1	87.9	
2	77.4	
3	95.2	
4	79.9	
5	95.4	
6	77.2	
7	85.8	
8		106.5
9		105.5
10		105.3
11		105.5
Average	85.5	105.7

Average current density, 0.494 milliampere per sq. cm.
Area of anodes, 9.4 sq. cm.

accord with accepted theories of corrosive processes, and the following experiments have been carried out in order to demonstrate that in general this is not the case, although under certain circumstances the tendency may be in that direction.

Four tests were made in which ingot iron was allowed to corrode naturally in the absence of oxygen, one test being in distilled water, two in tap water, and one in 10 per cent $Na_2 SO_4$ solution. Four tests were made in which the iron was allowed to corrode naturally in the presence of oxygen, two tests being in distilled water and two in tap water. Four tests were made in which the iron was allowed to corrode electrolytically in the absence of oxygen, the electrolyte being tap water in two of the tests and 10 per

cent Na_2SO_4 solution in the other two. Four tests were also made in which the iron was allowed to corrode electrolytically in the presence of oxygen, two tests being in tap water, and two tests in 10 per cent Na_2SO_4 solution.

The solutions were prepared practically free from oxygen by boiling down to about half their original volume in Erlenmeyer flasks. The iron test pieces were introduced during the boiling, and after the boiling was stopped the flasks were closed off from the air and a current of hydrogen free from oxygen was allowed to pass into the flasks as they cooled down, thus keeping the solutions under an atmosphere of hydrogen.

In the case of the natural corrosion tests in the absence of oxygen, the iron showed no corrosion at first, but after a day or two a few spots of greenish-black rust were noted, which gradually became larger as time went on, with the formation of a small amount of yellow ferric oxide. This was probably due to the fact that the air gradually diffused in through the rubber connections. In the case of the natural corrosion tests in the presence of oxygen, the rust was soon apparent and consisted almost entirely of the yellow ferric oxide. Thus we see that when oxygen is almost entirely excluded, the ferrous oxide predominates, and when oxygen is present, the ferric oxide predominates.

In the case of the electrolytic corrosion tests, the eight flasks were connected up in series, and a current of about 0.025 amperes allowed to pass for about 27 hours. At the end of this time the current was stopped and the anodes were taken out and weighed and the loss in weight determined. It was found that the corrosion efficiency was practically 100 per cent in all cases, calculating with iron having a valence of two. In the case of the four flasks from which air was excluded, the iron was practically all in the ferrous condition, the corrosion products having the pale green color of the hydrated ferrous oxide. Analysis of the corrosion products in one of the flasks gave 98.9 per cent ferrous iron, the slight oxidation being probably due to the unavoidable introduction of air into the flask during the removal of the electrodes for weighing. Through two of the other four flasks a current of air was allowed to bubble during the course of the electrolysis, and in those two flasks the corrosion products had the reddish yellow color of the hydrated ferric oxide, showing that the iron was largely oxidized to the ferric condition. The other two flasks were left open to the air, but air was not bubbled

through, and in these flasks the corrosion products had a darker color and when filtered off, dried, and tested with a magnet showed the presence of considerable magnetic oxide. Evidently then the corrosion had proceeded so fast that there was not enough oxygen present to oxidize the oxide completely to the ferric condition, but in the other case where air was bubbled through the solution, the solution was kept saturated with oxygen and so the oxide was converted completely to the ferric condition.

These results show that when iron corrodes electrolytically, it corrodes as the ferrous oxide and that the formation of higher oxides is due to the oxidation of the ferrous oxide by the oxygen of the air, the degree of oxidation depending on the rate of corrosion and the concentration of the oxygen. If the rate of corrosion is relatively rapid and the concentration of the oxygen is relatively low, there will be a predominance of the lower oxides, *i.e.*, the ferrous oxide and the magnetic oxide; on the other hand, if the reverse is the case, *i.e.*, if the rate of corrosion is relatively low, there will be a predominance of the ferric oxide.

The same explanation will apply to natural corrosion. In this case the rate of corrosion is very slow and so the ferric oxide predominates; and even when the oxygen is almost entirely excluded, the rate of corrosion is so slow that there is a slight formation of ferric oxide, although the ferrous oxide predominates.

From the foregoing it will apear that the character of the end products of corrosion does not depend essentially on the cause of the corrosion, but that either of the oxides may be produced, both in the case of self-corrosion, and in the case of electrolytic corrosion. It may, however, throw some light on the question in many circumstances, for the reason that the rate of natural corrosion of pipes imbedded in earth may usually be expected to be so low that practically nothing but the ferric oxides would be produced, there being enough oxygen in the soil waters to oxidize any ferrous iron that may be formed. In the case of electrolytic corrosion, however, this will not always be the result, the corrosion being so rapid, especially under bad electrolysis conditions, that the supply of oxygen in the ground waters will not be sufficient to oxidize all of the ferrous iron, and the result will be the formation of a considerable amount of magnetic oxide. This, however, will no doubt be largely affected by the depths of the pipe below the surface. The deeper the pipes,

as a rule, the less would be the available supply of oxygen, and the greater would be the tendency for the formation of the magnetic oxide. Pipes very close to the surface, even though corroding very rapidly by stray currents, might still form little if any magnetic oxide, because of the abundant supply of oxygen that would be available. Nevertheless, wherever a large preponderance of magnetic oxide exists, while it does not definitely prove that the corrosion has been due to stray currents, it may usually be regarded as a good indication that the rate of corrosion has been so great as to make it altogether probable that stray currents have been largely responsible, unless soil conditions, such as the presence of cinders, coke, chemicals, etc., are such that extremely rapid self-corrosion may be indicated.

7. *Relative Electrolysis in Different Kinds of Iron.* The question as to relative tendencies of different kinds of pipe to suffer damage due to electrolysis has often been discussed, and there appears to be a well-defined feeling in many quarters that a marked difference of this sort exists. It seems to be the general impression that cast iron pipes are much less susceptible to electrolytic damage than wrought iron or steel pipes. Experience indicates that cast iron pipe does offer less trouble from electrolysis than other kinds under most conditions. It has long been well known, of course, that certain kinds of iron are more resistant to self-corrosion than others, wrought iron, as a rule, being more durable under ground than steel, and cast iron suffering less than either. Since the experimental data presented later in this paper show that the natural corrosion is affected in a marked degree by the presence of stray currents, it might reasonably be supposed that different kinds of pipes would also suffer in widely varying degrees from stray current corrosion. In order to determine to what extent this might be the case, a considerable number of experiments have been carried out, using different kinds of iron that are employed in commercial service for underground pipes. Four kinds of iron were used, namely, ingot iron, which is the purest commercial iron known, wrought iron, machine steel and cast iron. Two series of experiments were run on cast iron, in one of which the cast iron was machined to a clean surface and in the other the iron was used just as it came from the mold, without removal of the scale. The test specimens weighing about 30 grams each were placed in a red clay soil practically saturated with water and run in series on a constant current so that the same number of ampere-hours was discharged

from each test specimen. The results are shown in Table VII. Since the current in all specimens was the same, and the size of the test specimens practically the same, giving about 0.2 milliamperes per sq. cm., the figures shown in the column under "electrical loss" are directly comparable for the different kinds of iron, and show the relative tendency of the iron to corrode electrolytically under conditions of the test.

TABLE VII

COMPARATIVE CORROSION EFFICIENCY FOR INGOT, WROUGHT AND CAST IRON AND MACHINE STEEL

No.	Total loss	Self-corrosion	Electrical loss (Check in can)
	1—INGOT IRON		
0	1.704 g.	0.015 g.	1.689 g.
3	1.678	0.033	1.645
4	1.848	0.051	1.797
5	1.669	0.031	1.638
6	1.791	0.043	1.748
7	2.243	0.046	2.197
8	1.665	0.041	1.624
9	1.583	0.074	1.509
10	1.688	0.036	1.652
11	1.713	0.060	1.653
12	1.706	0.033	1.673
13	1.676	0.042	1.634
14	2.167	0.055	2.012
15	1.661	0.028	1.633
16	1.679	0.076	1.603
17	1.674	0.046	1.628
18	1.648	0.058	1.590
19	1.647	0.057	1.590
		Ave. 0.046	Ave. 1.695
	2—MACHINE STEEL		
20	1.658	0.052	1.606
23	1.734	0.076	1.650
24	1.827	0.062	1.765
25	1.721	0.066	1.655
26	1.672	0.064	1.608
27	1.694	0.076	1.618
28	1.684	0.113	1.571
29	1.756	0.087	1.669
30	1.644	0.031	1.613
31	1.653	0.046	1.607
32	1.792	0.066	1.726
33	1.761	0.059	1.502
34	1.686	0.033	1.653
35	1.695	0.063	1.632
36	1.808	0.066	1.742
37	1.734	0.066	1.668
38	1.818	0.109	1.709
39	1.694	0.059	1.635
		Ave. 0.066	Ave. 1.652

No.	Total loss	Self-corrosion	Electrical loss (Checks in can)
	3—WROUGHT IRON		
40	1.713	0.160	1.533
43	2.203	0.077	2.126
44	1.789	0.065	1.724
45	1.712	0.063	1.649
46	1.689	0.117	1.572
47	1.842	0.094	1.748
48	1.756	0.116	1.640
49	1.693	0.069	1.624
50	1.659	0.048	1.611
51	1.201	0.114	1.087
52	1.701	0.124	1.577
53	1.661	0.068	1.593
54	1.852	0.055	1.797
55	1.684	0.068	1.616
56	1.646	0.050	1.596
57	1.712	0.073	1.639
58	1.713	0.076	1.637
59	1.840	0.080	1.760
		Ave. 0.084	Ave. 1.696
	4—CAST IRON, SURFACED		
60	1.807	0.120	1.687
63	1.700	0.305	1.395
64	1.846	0.108	1.738
65	1.757	0.283	1.474
66	1.769	0.177	1.592
67	1.746	0.079	1.667
68	1.808	0.136	1.672
69	1.939	0.082	1.857
		Ave. 0.161	Ave. 1.635
	5—CAST IRON UNSURFACED		
70	1.712	0.136	1.576
71	1.435	0.255	1.180
74	1.810	0.047	1.763
75	1.709	0.060	1.649
76	1.868	0.245	1.623
77	1.710	0.135	1.575
78	1.662	0.252	1.410
79	1.712	0.060	1.652
		Ave. 0.149	Ave. 1.553

An examination of these figures shows that there is but little difference in the amount of corrosion in the different kinds of iron. This is particularly true of the wrought iron, machine steel and machined cast iron, which show respectively 1.696, 1.652, 1.635 grams loss. The ingot iron showed a somewhat higher electrolytic corrosion than any of the others, which seems to be somewhat surprising in view of the fact that it has frequently been demonstrated that the self-corrosion in the case

of ingot iron is less than others. The least corrosion of all was in the case of the unfinished cast iron, and this is probably due to the protective effect of the scale, but even here the difference is hardly great enough to be considered of practical importance. The conclusion that must be drawn from these figures is that the efficiency of electrolytic corrosion of the different kinds of iron pipes is practically the same. If we examine the columns showing the self-corrosion in different kinds of iron we find very surprising differences. These check specimens were placed in the can along with the anodes and carefully shielded from the flow of current as in all previous cases. An examination of these data shows that the ingot iron gave the least self-corrosion of all, the average for all the specimens being 0.046 grams. Machine steel came next with a total natural loss of 0.066 grams; wrought iron is third with 0.084 grams; and last, and most surprising of all, the self-corrosion of the cast iron is very much higher, being 0.161 for the machined iron and 0.149 for the unfinished iron. This shows very little difference between the finished and unfinished cast iron in the matter of self-corrosion in the presence of current flow.

The relatively high rate of self-corrosion of cast iron as compared to the other kinds of iron tested is contrary to the generally accepted idea that cast iron is more resistant to self-corrosion than wrought iron. It is not improbable that this impression in regard to the superiority of cast iron has grown out of the fact that cast iron structures are usually made relatively heavy and they also tend to corrode more uniformly than wrought iron or steel, both of which factors would tend greatly to increase the life of the former. The principal cause of the greater rate of self-corrosion of cast iron appears to be the galvanic action set up between the free carbon and the iron. The carbon is distributed so uniformly throughout the mass, however, that no appreciable pitting results, and hence the corrosion is less conspicuous and also less important than the same amount of corrosion would be if not uniformly distributed, as is usually the case with most other kinds of commercial iron. It should be pointed out here that these tests were carried out in the same kind of soil as that used in securing the data of Table I, and the partial analysis there given shows it to be low in chlorides, sulphates, carbonates and nitrates. It was likewise free from cinders, coke, etc., and hence is not to be regarded as a very corrosive soil. It is shown later in this paper that the chemical constituents in

the soil have a marked influence not only on the total corrosion, but also on the pitting, or uniformity of the corrosion, so that it should not be assumed that the relative values given here will hold for all soils.

The foregoing results show that the different kinds of iron do not in themselves differ materially as regards their tendency to corrode electrolytically. It would appear from this that the differences noted in practise, particularly in favor of cast iron, are due to various other causes, as has already been pointed out by Prof. Ganz and others, namely, higher-resistance joints, higher specific resistance of the iron, the heavier walls, and a tendency to corrode more uniformly.

8. *The Effect of Certain Chemicals on the Corrosion of Wrought Iron in Earth.* When pipes are buried in the streets, they are subject not only to the action of the moisture and various natural constituents of the soil, but also to the effects of such chemicals as may result from the traffic on the streets, or from other sources.

A large amount of work has been done by other investigators on strips of iron immersed in aqueous solutions and it has been shown that the resulting corrosion is a function of the amount as well as the character of the chemical used. In many cases the tendency towards self-corrosion first increases with the concentration and later diminishes very rapidly, possibly to zero, when the concentration is sufficiently increased.

It is well known also that certain solutions, such as alkalis, chromates, etc., tend strongly to inhibit electrolytic corrosion, at least when such solutions are practically pure. Hayden has shown that solutions of chromates, for example, tend to produce passivity in iron and thus prevent electrolytic corrosion, but that this passivity is destroyed by the addition of a few hundredths of one per cent of a chloride or a somewhat greater quantity of sulphate. It was considered advisable to carry out a series of experiments with iron imbedded in earth to which various chemicals had been added.

For these experiments a number of acids, bases and salts as indicated in Table VIII were secured and two grams of each were added to 300 g. of distilled water. The solution was added to 700 g. of air-dried red clay, which had been sifted through a 20-mesh sieve. This earth contained initially about 5 per cent of moisture, so that the resulting mixture contained about 33 per cent water, which produced a fairly wet earth. The

TABLE VIII

EFFECT OF CHEMICALS ON CORROSION RESULTS

Chemical	Can No.	Solubility g. per liter	Solution used g. per liter	Chemical value g. per liter	Critical value g. per liter	Limiting value g. per liter	Efficiency of corrosion at 0.55 ma. per sq. cm.	Natural loss mg. per sq. cm. per day	Corrosion eff. obtained by Hayden 1% sol., 22 ma. per sq. cm.
								B. S.	
CH_3COOH......	2		5.715	0.0957			102.5	0.109	
$KMnO_4$....	28	63.4	5.715	0.0364	0.1	0.1–1.0	90.2	0.166	
$BA(NO_3)_2$......	34	92.0	5.715	0.0441			123.2	0.150	
$(NH_4)NO_3$.... ..	10	1924.0	5.715	0.0719	0–500	1155	116.3	0.265	37.8
$Na\ NO_3$.........	16	880.0	5.715	0.0677	0.1	632	104.2	0.152	
$K\ NO_3$.........	22	316.0	5.715	0.0571			89.6	0.238	25.0
$H\ NO_3$.....	4		5.715	0.0914			85.4	0.506	
Average.........							103.7	0.262	
$Ba\ Cl_2(2H_2O)$....	31	357.0	4.874	0.0479	0	374	106.0	0.136	
$Ca\ Cl_2(2H_2O)$....	25	427.0	2.890	0.0526			101.8	0.159	
$H\ Cl$...........	1		5.715	0.1579			101.6	0.270	
NH_4Cl....	7	372.0	5.715	0.1076	1.0	290	101.4	0.496	102.3
$K\ Cl$...........	19	340.0	5.715	0.0772	50.0	299	98.6	0.222	102.2
$Na\ Cl$..........	13	3582.0	5.715	0.0985	0	395	97.8	0.239	
Average.........							101.2	0.253	
$Na_2SO_4(1OH_2O)$..	18	194.0	2.520	0.0360	10.0	400	89.2	0.136	
$K_2\ SO_4$....	24	111.0	5.715	0.0661	0—	108	88.9	0.170	102.8
$Ba\ SO_4$..	36	0.002	5.715	0.0494			87.7	0.231	
$H_2\ SO_4$....... ...	6		5.715	0.1174			87.4	0.329	
$(NH_4)_2CO_4$.... ..	12	754.0	5.715	0.0873	0.200	534	86.0	0.316	102.7
$Ca\ SO_4(2H_2O)$...	30	2.0	4.520	0 0669	0		85.9	0.174	
Average.........							87.5	0.226	

TABLE VIII. *Continued.*

EFFECT OF CHEMICALS ON CORROSION RESULTS

Chemical	Can No.	Solubility g. per liter	Solution used g. per liter	Chemical value g. per liter	Critical value g. per liter	Limiting value g. per liter	Efficiency of corrosion at 0.55 ma. per sq. cm.	Natural loss mg. per sq. cm. per day	Corrosion eff. obtained by Hayden 1% sol., 22 ma. per sq. cm.
								B S.	
Ba $(OH)_2$ $(8H_2O)$	32	39.0	3.104 *	0.0365	0	3.1	93.1	0.322	
NH_4OH...... ...	8	526.0	11.770	0.6965			88.7	0.591	
K $OH(2H_2O)$.....	20	1120.0	3.480	0.0348			85.6	0.611	
Na $OH(1H_2O)$....	14	1090.0	3.942	0.0993			81.7	0.608	
H OH(Av.)......	3& 33				0.1	1.0	73.9	0.258	
Ca $(OH)_2$........	26	1.6	5.715	0.1556	0	0.67–1.35	73.5	0.195	
Average.........							82.7	0.431	
K_2 CO..........	21	1120.0	5.715	0.0834	1.0	1–10	89.3	0.306	2.75
$Na_2CO_3(10H_2O)$.	15	275.0	2.107	0.0201	1.0	10	85.4	0.394	
$(NH_4)_2CO_3$.... ..	9	1000.0	5.715	0.1225			81.7	0.561	38.2
Ca CO_3......	27	0.01	5.715	0.0719	0.0003	0.28	66.2	0.348	
Average.........							80.6	0.402	
$BaCrO_4$.........	35	0.004	5.715	0.0455			45.0	0.189	
$(NH_4)_2CrO$.. ...	11	405.0	5.715	0.0762			0.4	0.003	
$CaCrO_4$ $(2H_2O)$..	29	142.0	4.643	0.0600			0.3	0.136	
K_2CrO_4....	23	632.0	5.715	0.0593	0	0.1 up	0.3	0.163	
$Na_2CrO_4(10H_2O)$	17	813.0	2.829	0.0354			0.3	0.082	
CrO_3....	5	657.5	5.715	0.1143	0	0.01–0.05	0.2	0.122	
Average.........								0.116	

whole was thoroughly mixed and placed in a quart tin fruit can provided with a friction top.

The anodes were prepared as in experiments already described and vessels of water were placed in the cans as in previous experiments and the cans connected in series; first, in one group, finally, on account of increased resistance, in three. The current was adjusted daily to 0.005 ampere, which gave a current density of discharge of about 0.45 milliampere per sq. cm.

At the end of 85 days the experiment was discontinued, the cylinders cleaned as previously described and the losses computed.

In Table VIII the substances have been grouped according to the anions formed.

Since in a number of cases more salt was used than the water could dissolve, the solubility of each chemical has been indicated. This is followed by the number of grams of the anhydrous salt used, per liter of water. Then follows the chemical value of the solution, *i.e.*, the number of grams of salt per liter of water multiplied by the hydrogen value of the anion and divided by the molecular weight of the salt.

Then follow two columns of values obtained from Hein and Bauer's "On the Attack of Iron in Water and Aqueous Solutions."[5] The first is the concentration of solution giving maximum corrosion; the second the concentration producing passivity or minimum corrosion. Hein and Bauer suspended small iron plates in beakers of solutions of concentrations from zero to saturation. Their researches in this line are more extensive than any other work so far reported.

While their experiments cannot be compared with the one now recorded on account of differences in conditions, the values quoted may indicate at what part of the corrosion-concentration curve the present tests were made, from which we may form some estimate as to the manner in which the corrosion would have changed if the concentration had been varied. The efficiency of corrosion is given in the following column, and this is followed by the natural loss in milligrams per sq. cm. of surface of the iron per day.

Referring to the efficiencies of corrosion given in column 8, it will be seen that with the exception of chromium compounds the efficiencies of corrosion are comparatively high.

5. "*Mitteilungen aus dem Königlischen Material prüfungsamt.*", 1908 Berlin 26, 1.

All of the soluble chromates seem to protect the iron from electrolytic corrosion, though this protection is not quite complete. In the case of chromium trioxide the loss at the anode was slightly less than that of the check specimen. No significance should be attached to this result until after further investigation. The comparatively slight protection shown by barium chromate is no doubt due to its very slight solubility.

None of the other chemicals which Friend, Hein and Bauer or Hayden have found to render iron passive in solutions seem to have been effective. Indeed, excepting the chromates, there are but two values less than the average corrosion efficiency when distilled water was used.

The anodes in cans containing chromates were blackened and making the iron cathode in 2 per cent H_2SO_4 for half an hour did not remove the discoloration. The check specimens were not discolored in this way.

That the hydroxids did not protect the iron may have been due to the presence of materials in the soils which neutralized them. There was no doubt quite a little CO_2 in the soil, since it had been dried, crushed and sifted in the laboratory and had stood there in an open barrel for some time, and this may have been sufficient to counteract the effect of the hydroxids.

As will be seen by comparing columns 4 and 7, the concentrations used in the case of the hydroxids and carbonates were in nearly every case greater than those producing passivity when the solution alone acts on the iron. The difference in the results may be due to the effect of the earth on the solution or to the effect of the current. It seems clear, however, that the conditions which prevent self-corrosion are not in general those which will maintain passivity in the case of anodes discharging current at moderate current densities. There does not appear to be any very definite relation between the corrosion efficiency observed and the self-corrosion. The nitrates and chlorides, for instance, show respectively 103 and 101 per cent efficiencies of corrosion with corresponding value of self-corrosion of 0.262 and 0.263 mg. per sq. cm. per day. The hydroxids and carbonates show lower corrosion efficiencies, namely, 82 and 80 per cent respectively, but the natural corrosion is much higher, being 0.431 for the hydroxid and 0.402 for the carbonate. The soluble chromates show almost a complete absence of electrolytic corrosion; whereas the self-corrosion, although smaller than in the other cases, is by no means so small in proportion. It will be seen,

also, that the corrosion efficiencies observed do not agree with the values found by Hayden[6] and shown in column 10. While a part of this difference may be due to the differences in solution strength and current density, it is probably due for the most part to the fact that the tests in the present instance were carried out with anodes imbedded in earth, whereas the experiments of Hayden were carried out in water solutions.

It does not seem probable that a sufficient quantity of inhibiting chemicals can be added to the soil surrounding a buried pipe to protect it indefinitely at a reasonable cost. To render the pipe passive is one problem; to maintain it passive against fluctuating or even reversing currents, regardless of the action of the soil and the constantly changing soil waters on the soluble chemical, is quite another.

A phenomenon of importance which is not shown in the tabulated data, is the pitting of the iron. This is usually attributed to particles of impurities in the surface of the iron or to variations in the soil. In these experiments the virgin soil was dried, rolled and sifted through a 20-mesh sieve. Enough solution was added to nearly saturate the soil. All of the cylinders were cut from the same piece of Norway iron rod. It might be expected, therefore, that the pitting would be very similar in all cases. This, however, was by no means the case. The anodes from the nitrate cans were covered by a dark cheese-like layer which maintained the original form of the anode. When this was pared off the surface of the iron was nearly smooth, showing the fibrous structure of the wrought iron, but no pits. The anodes in the cans containing sulphates were corroded almost as uniformly, but the surface of the cleaned anodes was brighter and somewhat uneven, but with no marked pits. The surface of the anodes from the carbonate cans was more uneven. Pitting is noticeable in the case of the hydroxides and very marked in anodes from the cans containing chlorides.

As has been stated, the soluble chromates blackened the surfaces of the anodes but did not materially attack them otherwise. There are no marked differences in the appearance of the check specimens except that those from the chromate cans remained bright. So marked are the differences in the anodes that in most cases it is possible to classify them by their appearance, without reference to their numbers.

As underground pipes are almost always destroyed by pitting

6. *Journal of the Franklin Institute*, Vol. 172, pp. 295.

rather than by the amount of iron lost, a satisfactory means of preventing pitting would be of great value. The remedy most commonly suggested is the use of a more homogeneous iron. Without doubt this would reduce the corrosion due to local galvanic action, but the above experiments indicate that pitting of buried iron is very largely influenced by the nature of the electrolyte in the soil.

It may seem that for comparing the effects of different chemicals, quantities which are chemically equivalent should be chosen. A glance at columns 5 and 8 will show that in a number of cases practically equal corrosion efficiencies occur when the chemical values are very different. Indeed, so far as the tables go, there seems to be no relation between chemical values and corrosion efficiency.

It appears from these experiments that solutions which produce passivity when iron is immersed in them do not protect the iron against electrolytic corrosion when the solutions are in earth, and with the exception of the chromates, no chemicals here tried are of marked value in reducing corrosion. Also the action of iron in solutions is not a safe criterion of its behavior when the iron is made anode in earth containing these solutions.

9. *Efficiency of Corrosion in Soils from Different Sources*. While the foregoing experiments show the effect of the different factors which influence electrolytic corrosion in soils, they naturally raise the question to what extent these various factors are acting in the case of iron pipes subjected to electrolysis under practical conditions. This question seems to be best answered by actually carrying out experiments on electrolytic corrosion in a great variety of soils of different kinds, and gathered from widely different sources, at the same time maintaining the conditions as near to practical conditions as possible. In order to do this, corrosion tests were made on a large number of samples of soils which were gathered from various cities and sent to the Bureau of Standards at Washington for test as to their various physical properties. Ninety-seven such samples were used for these corrosion tests, which were taken from various places in Philadelphia, Pittsburgh, Erie and Apollo, Pa., St. Louis, Mo., Butte, Mont., and Albuquerque, New Mexico. Practically all of these soil samples were taken from excavations made for the purpose of examining pipes and were taken at about the same depth as the pipe in most instances. In all cases the samples were put at once into hermetically sealed cans

and kept therein until ready for test. For the purpose of making the corrosion tests, the soils were divided into two classes. Those soils from Philadelphia, St. Louis, Butte and Albuquerque were saturated with distilled water and kept so throughout the tests. The current density of the discharge averaged about 0.0002 ampere per square centimeter. The soils from Pittsburgh, Erie and Apollo, Pa., were tested with the same moisture content which they had when taken from the ground, and the current density was maintained at about 0.001 ampere per square centimeter. We thus have for one set a very wet soil and a rather low current density and in the other a rather high current density with what may be considered as roughly average moisture content, since at the time the samples were taken the soil was neither unusually wet nor unusually dry. The results of these efficiency of corrosion tests are given in Table IX. An examination of specimens 1 to 85, in which the earth was very wet and the current density low, shows quite high efficiencies of corrosion, the extreme ranges being 87.9 per cent for specimen No. 2 and 126.3 per cent for No. 30. All but two show values exceeding 100 per cent, while the great majority fall between 100 per cent and 115 per cent, the average of all being about 107 per cent.

The figures in the second group show much lower values, the extreme range being between 36.3 per cent and 104.3 per cent. Most of the values fall between 60 and 100 per cent, with an average for all specimens of about 76 per cent. The difference between the efficiencies of corrosion shown by the two series is evidently due partly to the lower moisture content and higher current density in the latter case. These results are in accord with the data already presented in which the effects of moisture and current density have been studied separately. It should be pointed out here that while the current density in the second series is higher than may be expected under average conditions in practise, it is no higher than would frequently be encountered under moderately severe practical conditions. From these and the preceding tests it will be evident that under average practical conditions we may expect the corrosion efficiency to be of the order of 100 per cent when the earth is very wet and the current density quite low, while as the moisture content is reduced or the current density increased, the corrosion efficiency falls off and will usually be found to range between 50 and 110 per cent, while in quite dry soils, such as might at times be encountered in prac-

TABLE IX

CORROSION EFFICIENCY TESTS ON SOILS FROM DIFFERENT SOURCES

A

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
1	2.294 g.	0.114 g.	2.180 g.	1.867 g.	116.8
2	1.811	0.170	1.641		87.9
3	2.147	0.062	2.085		111.9
4	2.244	0.195	2.049		110.0
5	2.327	0.090	2.237		119.8
6	2.203	0.117	2.086		112.1
7	2.156	0.075	2.081		111.9
8	2.244	0.175	2.069		111.0
9	2.273	0.089	2.084		116.7
10	2.363	0.133	2.230		118.8
11	1.881	0.064	1.817		97.3
12	2.103	0.174	1.929		103.4
13	2.173	0.126	2.047	1.876	109.2
14	1.992	0.025	1.967		104.8
16	2.584	0.280	2.304		122.8
17	2.186	0.041	2.145		114.4
18	2.207	0.032	2.175		115.9
19	2.052	0.086	1.966		104.8
21	2.058	0.091	1.967		104.8
22	2.187	0.130	2.057	1.871	109.9
23	2.168	0.203	1.965		105.0
24	2.091	0.044	2.047		109.4
26	2.239	0.078	2.261		120.9
27	2.398	0.112	2.286		122.3
29	2.091	0.068	2.023	1.895	107.0
30	2.497	0.108	2.389		126.3
32	2.190	0.044	2.146		103.6
33	2.130	0.079	2.051		108.4
34	2.068	0.061	2.007		106.0
37	2.310	0.170	2.140		113.2
38	2.114	0.097	2.017		106.4
39	2.362	0.085	2.277		102.4
41	2.300	0.025	2.275		120.2
42	2.313	0.155	2.158		113.7
43	2.161	0.150	2.011	1.913	105.0
44	2.148	0.094	2.054		107.3
45	2.202	0.031	2.171		113.4
46	2.105	0.182	1.923		100.7
47	2.257	0.101	2.156		112.8
48	2.489	0.351	2.138		111.7
49	2.126	0.022	2.104		110.2
50	2.177	0.121	2.056		107.3
51	2.188	0.122	2.066		107.9
52	2.305	0.104	2.201		116.1
53	2.200	0.148	2.052		107.3
54	2.250	0.228	2.022		105.7
55	2.108	0.052	2.056		107.4
56	2.330	0.117	2.213		115.6
57	2.252	0.115	2.137		111.7

TABLE IX—Continued

CORROSION EFFICIENCY TESTS ON SOILS FROM DIFFERENT SOURCES

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
58	2.206	0.156	2.050		107.2
59	2.258	0.247	2.011		105.2
60	2.194	0.133	2.061		107.8
62	1.318	0.054	1.264		66.2
63	2.201	0.143	2.058		107.6
64	2.242	0.068	2.174	1.866	117.2
65	2.224	0.157	2.067		116.3
66	2.295	0.060	2.235		121.0
67	2.085	0.045	2.040		109.9
68	2.164	0.060	2.104		113.4
69	2.276	0.181	2.095		112.9
71	2.225	0.096	2.129		114.7
72	2.210	0.156	2.054		110.8
73	2.152	0.020	2.132		104.9
74	2.070	0.096	1.974		106.4
75	2.190	0.100	2.090		112.6
76	2.062	0.038	2.024		109.2
77	2.200	0.072	2.128		114.6
78	2.089	0.151	1.938		104.4
79	2.063	0.114	1.949		105.1
81	2.286	0.064	2.222		119.8
82	2.152	0.157	1.995		107.5
83	2.330	0.135	2.195		108.3
84	1.706	0.188	1.518		81.8
85	2.062	0.003	2.059		111.0
	B—Pittsburgh, Pennsylvania, Soils*				
	4.600	0.207	4.393	4.97	88.4
	5.100	0.177	4.923		99.2
	3.953	0.295	3.658		74.7
	2.780	0.220	2.560		51.6
	5.210	0.030	5.180		104.3
	4.368	0.005	4.363		87.8
	5.195	0.140	5.055		101.6
	2.822	0.270	2.552		51.4
	3.005	0.140	2.865		57.7
	4.435	0.145	4.290		86.4
	3.519	0.546	2.973		67.2
	4.272	0.545	3.727		72.0
	C—Erie, Pennsylvania, Soil*				
	4.932	0.185	4.747	4.75	99.9
	3.499	0.250	3.249		68.2
	4.692	0.255	4.437		94.0
	3.595	0.129	3.466		72.9
	4.777	0.245	4.532		74.4
	18.180	1.451	17.729		80.7
	7.531	0.040	7.491		36.3

*Current density, one milliampere per square centimeter.

Nos. 1 to 37 inclusive taken from Philadelphia. Nos. 38 to 47 taken from Norristown, Pa. Nos. 48 and 49 from Albuquerque N. M. Nos. 50 to 84 from St. Louis, Mo

tise, a much lower figure might occur. We are convinced that under average conditions of soil moisture, and with current densities that may be expected in localities where electrolysis conditions may be considered moderately severe, a corrosion efficiency between 50 and 110 per cent will usually prevail. It will be seen also from the foregoing data that the decrease in corrosion efficiency due to increased current density is by no means as rapid as the increase in current, so that within the limits of current density that will usually be encountered in practise the actual amount of corrosion will be found to increase with increase of current.

The question may well be raised as to the reliability of corrosion efficiency experiments carried on in earths in the laboratory, and the extent to which such results may be considered as representing what would take place in the earth under normal conditions. In general, however, it will appear that experiments made in the laboratory are much more satisfactory for studying the laws of corrosion, because conditions can then be much more readily controlled, and it is simply necessary to determine whether or not the laws of corrosion are substantially the same in the case of experiments on iron imbedded in small samples of soil as they would be if the iron were imbedded in the earth out of doors, all other conditions being the same. This would probably not be true if the experiments were continued over a great length of time during which certain soluble constituents of the soil in the laboratory specimens might become exhausted by the corrosive processes, but we have ample reason to believe that experiments thus made and extending over a comparatively short time represent quite closely what may be expected to take place in the case of pipes under actual conditions. Numerous experiments have been made on specimens of iron imbedded in the earth out of doors in order to check this conclusion and to guard against any serious error that might be introduced by possible conditions of the soil. Some of the data bearing on this have already been given in the earlier part of this report relating to the effects of depth of burial and of current density on efficiency of corrosion, which show that for similar conditions the results for the outdoor tests do not give results materially different from the indoor tests. Another series is given in Table X. In this case a number of specimens of iron were buried in the earth out of doors and caused to carry current for several months, and the efficiency of corrosion was

determined. The current density varied considerably during the experiments, due largely to change in resistance of the soil, but on the whole the range of current density averaged about the mean of the values used in the tests on effect of current density given above. The moisture content, of course, varied considerably from time to time.

An examination of Table X shows that the efficiencies of corrosion in these outdoor tests ranged between approximately the same limits as those carried on indoors for similar ranges of moisture and current density. These data afford additional evidence that the results of the corrosion efficiency experiments carried out on samples of iron imbedded in soils in the laboratory

TABLE X
EFFICIENCY OF CORROSION
SPECIMENS BURIED IN GROUND OUT OF DOORS

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
1	15.719g.	0.286g.	15.433g.	74.9
3	12.153	0.286	11.873	72.8
5	4.425	0.282	4.143	61.5
6	5.879	0.282	5.597	73.9
7	5.894	0.280	5.614	80.0
10	6.374	0.280	6.094	96.3
11	2.364	0.278	2.086	83.3
12	3.310	0.278	3.032	76.8
				Ave. 77.9

are of substantially the same order of magnitude as they would be if the iron had been buried out of doors.

10. *Causes of Variations in Efficiency of Corrosion.* The causes which give rise to corrosion less than the theoretical amount according to Faraday's law have been the subject of much research by numerous investigators in connection with studies of passivity in iron. Numerous theories have been evolved, but comparatively little is definitely known in regard to this subject. The subject is too complicated and would lead to too much theoretical detail for us to go into here. On the other hand, no attention has been given to the influences that may be responsible for corrosion efficiencies greater than 100 per cent. and in view of the frequency with which these high efficiencies of corrosion occur it seems well to present here very

briefly a few comments as to the possible causes that may be responsible for these high values.

It has been seen that the efficiency of corrosion of iron imbedded in earth in many cases exceeds 100 per cent, although we have not been able to confirm the results of other investigators previously referred to in this paper who have reported electrolytic corrosion amounting to several times the theoretical value. The highest values which we have found in our experiments have been of the order of 150 per cent, but for the most part the corrosion has not been greater than 20 per cent in excess of the theoretical amount. The very large number of cases, however, both among the tests already described and among those that follow, in which the corrosion efficiency exceeds 100 per cent, even after careful correction has been made for self-corrosion, indicate quite clearly that the loss of iron due to the discharge of electric current is in many cases appreciably greater than the theoretical amount. This is a matter of great importance and is being given special attention with the view of throwing further light on its causes, but much yet remains to be done before the phenomena can be properly understood.

Several causes suggest themselves as possible factors in producing this high efficiency of corrosion, some of which are discussed below.

a. *The Formation of New Galvanic Couples.* It is well known that when iron corrodes in the presence of water and oxygen, oxides of iron are formed as end products. Under most underground conditions these will be deposited at the surface of the iron in more or less irregular contact with the iron. These oxides are fairly good conductors and are also electro-negative against iron, so that when a particle of iron oxide comes in actual contact with the iron, a galvanic element is formed which tends to corrode the adjacent iron. It seems not improbable, therefore, that when a clean piece of iron is subjected to the discharge of electric current the formation of the iron oxide which results from the initial corrosion may set up galvanic couples which did not before exist and thus greatly increase the self-corrosion on the specimen.

The following experiments were carried out to gain an idea of the effect of the initial corrosion products on subsequent electrolytic corrosion and on the self-corrosion of the specimen. In this experiment, twelve two-quart tin cans were coated outside with paraffin, and a layer of heavy paraffined paper placed

over the sides. The cans were then nearly filled with red clay which had been air-dried two months, and sifted through a 20-mesh sieve; 300 g. of distilled water was added to 700 g. of this sifted earth, and the whole thoroughly mixed before it was packed in the cans. This earth was nearly saturated with water. For anodes and check specimens cylinders of $\frac{1}{4}$-inch (6.3 mm.) Norway iron, 2 in. (5.08 cm.) long, were used. The cylinders were carefully cleaned and placed vertically in the cans, the anodes in the center and the check specimens close to the side, and carefully shielded from current flow. A small vessel of water was placed within each can to retard evaporation of the moisture in the earth.

The twelve cans were then connected in series on a 115-volt circuit, the cans serving as cathodes. The current was kept practically constant at 10 milliamperes.

At the end of 429 hours, eight cans were removed from the circuit. Four of these were set aside unopened. From the other four the cylinders were removed, cleaned, weighed, and replaced, and the four cans were then replaced in circuit.

At the end of 686 hours more, the cans were opened, the cylinders cleaned, weighed, and the losses computed. When the cylinders were washed in warm water, practically all of the rust came off, so that it was necessary to clean them electrolytically for but a few minutes to obtain a bright surface.

The corrosion of the anodes was more uniform than in most previous experiments, but the corroded surface was somewhat uneven, the loss being greatest near the centers of the cylinders. There was practically no pitting of the check specimens.

The results of the experiments are shown in Table XI. Here the specimens are divided into three groups, *A*, *B*, and *C*. In group *A* the current was kept on the specimens during the first period of 429 hours and then switched off, but the specimens were permitted to stand in the soil undisturbed during the second period of 686 hours, after which they were taken out and weighed and the efficiency of corrosion determined. In this case, if the initial corrosion due to the electric current tended to accelerate self-corrosion, we should expect a higher efficiency of corrosion than if the specimens had been removed as soon as the current was shut off. In group *B* the specimens also carried current during the first 429 hours, but were removed from the earth, cleaned and weighed as soon as the current was shut off and then put back in circuit again. If the self-corrosion is

greater, due to the initial electrolysis, we should expect that the efficiency of corrosion would be smaller for the first period in group *B* than was obtained for group *A*. The table shows that such was the case, although the difference is quite small and

TABLE XI

EFFECT OF INITIAL PRODUCTS ON SUBSEQUENT CORROSION

Area of exposed metal, 7.6 sq. cm. Current density about 1.2 milliamperes per sq. cm. Moisture in soil about 30 per cent.

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
		Group A		
2	4.270g.	0.085g.	4.185g.	102.8
6	4.408	0.085	4.323	106.3
7	4.365	0.085	4.280	105.2
12	4.370	0.085	4.285	105.3
				Ave. 104.8
		Group B. 1st Period		
1	4.230	0.045	4.185	102.8
3	4.226	0.045	4.181	102.7
13	4.225	0.045	4.180	102.7
14	4.273	0.045	4.228	103.8
				Ave. 103.0
		Second period		
1	6.316	0.080	6.236	87.8
3	6.645	0.080	6.565	92.5
13	6.475	0.080	6.395	90.1
14	6.823	0.080	6.743	95.0
				Ave. 91.4
		Group C		
4	11.185	0.149	11.036	99.0
5	10.658	0.149	10.509	94.3
8	10.275	0.149	10.126	90.8
9	10.945	0.149	10.796	96.9
				Ave. 95.2

may possibly be due to other causes. By cleaning these specimens and putting them back in the same soil in which they had previously run and maintaining the same current flow as before during the second period we could determine whether there was

any marked change in the efficiency of corrosion due to changes in the soil caused by the flow of current. The table shows that there was a marked difference here, the efficiency of corrosion being much lower during the second period than during the first. In group *C* the specimens were permitted to remain in circuit during both the first and second periods without interruption.

In comparing the results obtained from these three groups it is significant that the highest apparent efficiency of corrosion was obtained when the current was allowed to flow for a time and then removed and the specimen allowed to remain in the earth subjected to the action of self-corrosion during the second period. The next largest apparent efficiency was obtained when the specimens were cleaned and weighed at the end of the first period immediately after the stopping of the current. The lowest efficiency was obtained when the cleaned specimens of group *B* were returned to the same earth which had been previously used and again connected in circuit during the second period. Further, group *C*, which ran continually throughout the first and second periods, showed an intermediate value of corrosion efficiency. These results appear to show that there are two opposing tendencies at work, one of which is to increase the corrosion efficiency as in group *A*, due to some cause associated with the flow of current, and the other a tendency to decrease the corrosion efficiency as in group *C*, due perhaps to depletion of certain ingredients in the electrolyte. Other experimental data given in this paper indicate that this tendency for the efficiency of corrosion to decrease with time may be due either to the exhaustion of dissolved oxygen or to a loss of moisture by the earth.

The check specimens used in these experiments also show the effect of current flow on the self-corrosion of check specimens placed in the cans along with the anodes. Examining the data for group *B* under the column headed "Self-corrosion", we find that during the first period the rate of corrosion was less than after the check specimens had been cleaned and returned to the same cans. By comparing the self-corrosion in group *A* with those in groups *B* and *C*, the tendency is seen to be the same and even more marked. Further, by comparing the self-corrosion of group *B* with that of group *C* we find that, although the total flow of current is the same, the corrosion is considerably greater in the latter. Since those of group *B* were removed once and

cleaned, while those of group C were not, this result seems to support the theory that the presence of a small amount of initial corrosion tends to stimulate the self-corrosion throughout the remaining period of the test. It should be borne in mind, however, that the figures on which this statement is based are subject to such large variations that they should not be accepted as conclusive until they have been repeatedly verified.

b. *The Depolarizing Effect of Oxygen.* According to the electrolytic theory of corrosion all iron contains sufficient differences in physical or chemical structure at different points on its surface to set up local galvanic elements which are supposed to be responsible for self-corrosion. Under ordinary conditions of self-corrosion, therefore, there will be certain points on the surface which will be anode points discharging current into the electrolyte and corroding the iron and there will also be, near by, cathode points at which the current reenters the iron. The amount of corrosion which results from these couples will, of course, depend upon the resistance of the local circuit as well as on the effective difference of potential which exists between adjacent points. When current flows in these local paths there is a tendency to form a film of hydrogen at the cathode points which diffuses but slowly, and this not only sets up a counter electromotive force but it likewise introduces a large amount of additional resistance into the local circuit. In consequence of this the self-corrosion may be said to inhibit itself to a very considerable extent. If now we superpose on this specimen an electric current, making the specimen anode, more or less oxygen will be liberated near the surface of the metal which may react with the hydrogen, thus in effect depolarizing the local galvanic action and permitting much greater self-corrosion in the case of a specimen discharging current than in a case of a similar specimen not discharging. This excess of self-corrosion would always appear, due to the main current flowing, and would thus increase the apparent efficiency of corrosion. It is easy to see how this effect could increase the efficiency of corrosion from a low value up toward 100 per cent, although it would not in general tend to make the corrosion efficiency greater than 100 per cent.

c. *Non-Uniform Corrosion of the Iron.* When iron corrodes it is always with greater or less irregularity. Pits may be formed in which a small hole on the surface may communicate with a large chamber below, and this pitting may pursue such an

irregular course as to eat entirely around particles of iron, causing them to fall away from the test specimen. This seems particularly likely to happen in the case of very impure metals, which often exhibit a more or less honeycombed aspect after long-continued corrosion. Since the efficiency of corrosion is always determined from the net loss of weight, any particles of iron that might be dislodged in this manner would be charged against the current and in this way the corrosion efficiency might easily be made to appear larger than 100 per cent.

d. *Circulation of the Electrolyte.* It is well known that if the electrolyte surrounding a piece of iron be kept in constant circulation the amount of self-corrosion which results will be greater than if the electrolyte remains practically still. When an electric current flows through an electrolyte it causes a migration of the ions which may increase the self-corrosion of the iron in a manner analogous to circulation of the electrolyte. Particularly, in the case of an anode there is a tendency for the acid radicals such as Cl, SO_4, etc., to concentrate near the anode surface and it is well known that liquids containing large amounts of these radicals, particularly the chlorine, produce very rapid corrosion of the iron. Here again any excess of self-corrosion which would be produced would be charged against the electric current and a high efficiency of corrosion would result. It is not improbable that any or all of the above-mentioned causes may be operating in certain cases to produce a high efficiency of corrosion. However that may be, it has been definitely established that if a check specimen is imbedded in the earth along with the anode the self-corrosion will always be much higher than if the check specimen is imbedded in the same earth but in a separate vessel. This is true even when ample precautions are taken to shield the check specimens from the flow of electric current. This is shown by the following series of experiments, which is typical of a great many which have been carried out. The anodes were buried in the center of a quart tin can filled with earth, the can itself serving as the cathode. The check specimen was placed in the earth near the cathode and shielded from current flow by means of a glass shield semi-cylindrical in form and of considerably greater diameter and length than the check specimen. The arrangement is shown in Fig. 1. In many of these experiments, in addition to the check specimens placed inside the can, a second check specimen was also placed in the same kind of earth with the same moisture

content, but placed in a separate vessel through which no current passed. A few of these data, which are typical of all, are given in Table XII.

From this table it will be seen that the average self-corrosion on the check specimens placed in the can carrying current was roughly 2.7 times that on the specimens in the cans through which no current passed, while the time in the latter case was 1.7 times that in the former, thus making the average rate of self-corrosion about 4.6 times as great in the can carrying current as in the one which carried no current. Further, it seems altogether probable from the foregoing discussion of causes of increased corrosion efficiency that the self-corrosion on the anode itself would be considerably greater than that on the check

TABLE XII

EFFECT OF CURRENT FLOW ON SELF-CORROSION

Check No.	Loss of check with iron carrying current 49 days	Loss of check in separate vessel 83 days
7	0.075 g.	0.041 g.
14	0.025	0.022
21	0.091	0.025
28	0.038	0.022
35	0.048	0.045
42	0.155	0.057
63	0.143	0.063
83	0.135	0.018
84	0.118	0.014
	Ave. 0.092	0.034

specimen placed inside the same can, so that even though the electrolytic corrosion proper were to take place strictly in accordance with Faraday's law we should nevertheless obtain an experimental result indicating an efficiency considerably greater than 100 per cent.

In view of the foregoing, therefore, it does not appear that we have any reason to suppose that the electrolytic corrosion proper does not take place in accordance with Faraday's law, even though a corrosion efficiency of much more than 100 per cent is indicated. Nevertheless in computing corrosion efficiency it is proper to charge all of this excess of self-corrosion against the electric current, since in the absence of the current it would not have occurred, and the corrosion directly chargeable to the current includes all of that which results from the passage of

the current, whether due directly to the current or to secondary causes brought into action by the current flow.

11. *Effect of Very Low Voltage.* In all of the foregoing experiments, although the current density has often been reduced to quite low values, the voltage impressed upon each pair of electrodes has in general been somewhat high, being of the order of several volts in most instances. This has been due to the fact that the small size of most of the electrodes used gave rise to so high a resistance in the earth that voltages of this order were necessary in order to produce the desired current density. Although there is no theoretical reason why the efficiency of corrosion should vary with voltage except in so far as it affects the current density, nevertheless it seemed very desirable to carry out a few experiments on very low voltages, particularly below one volt, in order to determine whether the efficiency of corrosion would be materially different with such extremely low voltages from what it is on the higher values. Accordingly, three cells were made up, using tap water as an electrolyte and thin sheet iron electrodes separated by several sheets of filter paper. This gave a very low resistance between the electrodes and made it possible to secure sufficiently large current on much lower voltages than had been possible in the case of specimens buried in soil. One of these cells was run on a constant potential of 0.1 volt, another on 0.6 volt, and the third at one volt. Current measurements were made at frequent intervals and the ampere-hours determined. The results are shown in Table XIII. It will be seen by reference to this table that the efficiencies of corrosion are comparatively high, being highest in the case of the one-volt cell and lowest in the case of the 0.6-volt cell, and intermediate in the case of the 0.1-volt cell. The current densities are given in the table and are seen to be extremely low, the lowest being but 0.003 of an milliampere per square centimeter. These results show quite clearly that there is no reason to expect that the corrosion efficiency changes materially at any critical value of voltage within a range that is of any practical consequence in the negative return of street railway systems.

II. EARTH RESISTANCE

The foregoing experiments show what may in general be expected under different conditions as to the discharge of current from iron electrodes buried in soils. In practise, however,

when investigating electrolysis conditions, we are not dealing with known conditions of current flow, since it is in most cases impracticable to measure directly leakage currents at any point in the soil without resorting to measures that are too tedious and expensive for most work. We have, on the contrary, certain easily determined voltage conditions throughout the negative railway return system, and hence, in order properly to interpret the data above presented relating to laws of corrosion, it is necessary to take into consideration the effect of earth resistance on the stray currents that may be carried by the pipes and discharged by them into the earth under known conditions as to potential differences in the network. It is not the purpose of this paper to go into detail in regard to the matter of earth resistance, as this is to be treated somewhat fully in another

TABLE XIII
LOW VOLTAGE TEST

Plate No.	Loss total	Electrical loss	Theoretical loss	Corrosion efficiency	Current density milliamp. per sq. cm.	Voltage
1	0.496 g.	0.456 g.	0.467 g.	97.7	0.051	1.0
2	0.153	0.113	0.127	89.0	0.014	0.6
3	0.062	0.022	0.024	91.7	0.003	0.1

Area of anode, 47.47 sq. cm.
Ave. natural loss of anode 40 mg.

paper by the authors in a publication of the Bureau of Standards. The great importance of the subject of earth resistance, however, in relation to electrolytic corrosion in soils, makes it desirable to present here very briefly a few fundamental principles in regard to the resistance of soils and its relation to stray current electrolysis.

It is obvious that if the soil surrounding the pipe network possessed infinite resistance, there would be no trouble from electrolysis, since in that case no stray currents could leak from the tracks and hence find their way into the pipe. On the other hand, if the earth possessed zero resistance, we would also have no electrolysis, since in that case the earth would short-circuit the pipes and prevent them from taking up the stray currents. Somewhere between these two extremes we will obviously have a value of earth resistance which, in any given case, would pro-

duce a maximum of electrolysis trouble. The value of this resistance required to give a maximum electrolysis undoubtedly varies greatly with conditions; such as geometrical form of the pipe and track networks, kinds of joints used in pipes, size of pipes, resistance of rail return, and numerous other factors. We feel confident, however, from observations made under practical conditions, that in most, if not all cases, the resistance of the earth will be found much higher than that required to produce maximum electrolysis, so that in general we may expect the electrolysis to be greater the lower the resistance of the earth. With a view of giving an idea of what may be expected in the way of earth resistance in practise, we present below a summary of some investigations which we have made in regard to variation of earth resistance with varying conditions, and following that we have given the results of a considerable number of earth resistance measurements made on a variety of soils taken from widely scattered sources. In making these earth resistance measurements several different methods were used, in some of which the earth was measured in place without being disturbed, while in other cases the samples were taken to the laboratory, packed in glass cylinders and the resistance measured between plastic amalgam electrodes pasted on the ends of the cylinder, the voltmeter-ammeter method with alternating current being used. In a good many cases both methods were used and the results were found to check in a very satisfactory manner. In making the earth resistance measurements in place, two excavations were made side by side to a depth of several feet, leaving a portion of undisturbed earth several inches in thickness between the two excavations. The sides on this undisturbed portion were made approximately parallel and fairly smooth, and small electrodes a few inches in diameter placed on the opposite sides. These electrodes were then surrounded by guard rings of sufficient diameter to assure practically parallel lines of current flow between the two electrodes. The resistance of the earth between the electrodes was then measured by means of voltmeter-ammeter methods as in the laboratory, alternating current being used for the purpose. In making these measurements care was taken to keep the electrodes and the guard ring not only at the same potential, but also to see that there was no displacement of phase between the e.m.fs. applied to them.

In making the tests in the laboratory, preliminary experiments showed that much more satisfactory results could be obtained

by compressing the earth in the testing machine to such a point that further increase in pressure caused practically no variation of resistance. It was found, and will be shown by the curves below, that with increase of pressure a point is soon reached beyond which the resistance varies but slightly with further increase in pressure. Careful comparison of results obtained by first measuring the resistance in place, in the ground, and later in the same earth in the laboratory, indicated that they were practically the same whichever method was used, and since the method of measuring the resistance in the laboratory was so much more rapid and convenient, this method was used for the great majority of measurements that are presented below.

12. *Effect of Moisture Content on Earth Resistance.* Moisture content is one of the controlling factors in earth resistance. In Table XIV is given a series of resistance measurements taken on a

TABLE XIV

RELATION BETWEEN THE AMOUNT OF MOISTURE IN THE SOIL AND ITS SPECIFIC RESISTANCE

Per cent moisture (in terms of dry earth)	Specific resistance ohms per centimeter cube
5.0	2,340,000
11.1	237,400
16.7	13,880
22.2	6,835
33.3	5,400
44.5	4,725
55.6	4,870
56.7	5,197
77.8	5,045

sample of red clay soil with varying moisture content, which may be regarded as more or less typical. For making each measurement a new sample of thoroughly dry earth, dried at 105 deg. cent., was taken and the required amount of moisture added, the percentage of moisture being expressed in terms of the dry earth. It will be seen that above about 22 per cent of moisture the resistance remains practically constant, but below this value, the resistance rises very abruptly with decrease of moisture content, and at 5 per cent of moisture the resistance has risen to considerably over four hundred times its value when the soil is saturated. This shows that the actual current flow to and from a pipe imbedded in soil is dependent in vastly greater degree on the moisture content than on the potential difference between the pipe and surrounding structure, and points to the fact that a potential difference which might be

perfectly safe in a high and well drained locality might be sufficient to give rise to a great deal of damage in a low and damp locality. This tendency has of course been well recognized, but it has not been given the consideration which it deserves. Cases frequently arise in which this fact might well be treated as an important factor in determining the location of a railway substation, and particularly the points at which insulated radial return feeders might best be connected to the tracks.

Another important practical aspect of this change in resistance with moisture content is its effect on the distribution of potential drops throughout the negative railway return area. Since the various parts of the pipe system are buried at different depths and are very irregularly located with respect to the tracks, it is evident that changes in the moisture content with depth will exert a marked influence on the distribution of the resistance in the path of the leakage current, which in turn will greatly affect both the magnitude and distribution of the potential gradients throughout the system. For this reason not as much reliance should be placed on voltage surveys made at extremely wet and more especially at very dry periods as on those taken under more nearly average moisture conditions.

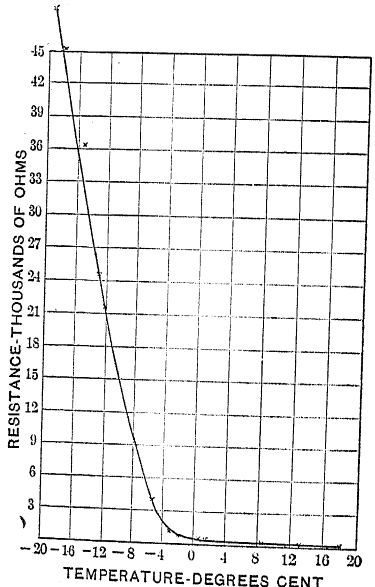


FIG. 8—RESISTANCE-TEMPERATURE CURVE

13. *Effect of Temperature on Earth Resistance.* The effect of temperature on the resistance of soil was determined throughout the range from about 18 deg. cent. to − 18 deg. cent. (0 to 65 deg. fahr.). For this purpose a moist soil was used and was placed in a vessel surrounded by an ice-chamber in which a mixture of ice and salt was placed and the whole was allowed to stand until the temperature had reached about − 18 deg. cent., the resistance being measured from time to time by means of electrodes which were imbedded in the sample of earth and rubber-covered leads brought out. The temperature of the

earth was taken at the same time each resistance measurement was made, an ordinary mercury thermometer inserted in the center of a hollow electrode being used. The results of these resistance measurements, as a function of temperature, are given in Table XV and are plotted in Fig. 8. By reference to the curve it will be seen that the resistance varies throughout very extreme ranges, even within the ranges of temperature variation that commonly occur in this country. Above freezing, the resistance variation is much less marked, but even here we find that the resistance at zero deg. cent. is approximately 2½ times its value at 18 deg. cent. At about the point at which the soil water begins to freeze there is tremendous increase in the temp-

TABLE XV

EFFECT OF TEMPERATURE ON RESISTANCE OF SOIL

Soil No. 32. Moisture 18.6 per cent. Specific resistance at 20 deg. cent. 6260 ohms per cu. cm.

Temperature cent.	Resistance ohms
18.0	224
13.0	286
8.5	398
1.5	458
1.0	462
0.0	542
− 2.0	940
− 3.0	1,185
− 5.5	4,340
−12.0	21,700
−13.0	24,600
−15.0	36,200
−18.0	45,000
−19.0	48,900

erature coefficient of resistance, and as the temperature becomes lower the resistance rises enormously, and at − 18 deg. cent. the resistance is seen to be over two hundred times as great as at 18 deg. above zero.

This enormous variation of earth resistance with temperature is of considerable practical importance and indicates that in moderately cold weather such as prevails in the northern cities, comparatively little trouble from electrolysis may be expected. This is not due primarily to the higher resistance of the earth immediately surrounding the pipes, since the pipes are usually located at a sufficient depth so that the temperature of the earth immediately surrounding will not reach the lower values

used in this experiment. The real reason for the diminution of electrolysis trouble with the fall in temperature is the reduction of leakage current from the rails. It will be evident that when the ground is frozen even but a few inches deep, the resistance of the earth immediately surrounding the rail becomes enormously increased, and the leakage of stray currents into the earth is thereby correspondingly reduced. And since the rise in resistance with even a few degrees of frost may be many fold, it is apparent that but a thin layer of frozen earth about the rail would be necessary in order to produce a very marked increase

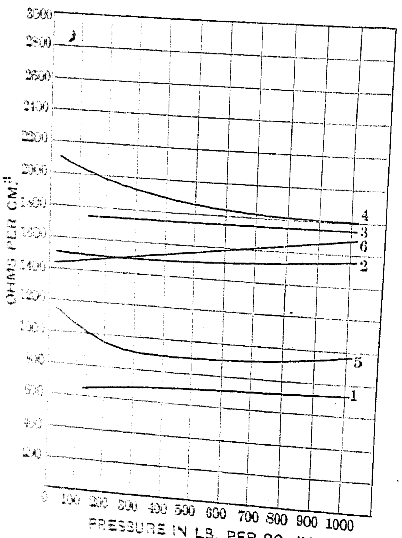


FIG. [illegible]—SPECIFIC RESISTANCE-PRESSURE CURVES OF EARTH
1—[illegible] clay, sample 51; 2—black humus, sample 52; 3—black humus, sample 59; 4—yellow clay, sample 56; 5—sand and humus, sample 64; 6—yellow clay and sand, sample 58

in the total resistance of the path of the leakage current. This reduction in electrolysis troubles in cold weather due to increase in resistance of the earth is further augmented by the increase in the conductivity of the rail return which takes place at the lower temperature, which may amount to as much as 15 or 20 per cent, and is sufficient, as a rule, to compensate for the increased load which usually prevails during the cold period.

[illegible] also be pointed out here that the effect of variations [illegible] with depth on the resistance of earth will have an [illegible] the distribution of potential gradients in the earth very

similar to variations in moisture content referred to above. For this reason it is preferable not to make voltage surveys at times when extremely low temperatures prevail.

14. *Effect of Mechanical Pressure on Earth Resistance.* Of considerable interest, although of much less practical importance, is the effect of mechanical pressure on the electrical resistance of earth. As already stated, when pressure is applied to a sample of earth its resistance is but little affected as a rule, after a certain relatively low value of pressure is reached. This is shown in Fig. 9, which gives resistance-pressure curves for a number of different soils from various sources. The range of pressures here is for the most part between twenty and one thousand pounds per square inch, and the variations in resistance between these limits are surprisingly small. Numerous measurements of the resistance of earth two or three feet below the surface before being disturbed, using the guard ring method, and subsequent measurements of the same earth in the laboratory, under pressure, show that the resistance at a few hundred pounds pressure per square inch is substantially the same as that of the undisturbed earth.

15. *Other Factors Affecting Current Flow.* There are other factors also which affect the resistance of soils, such as its mechanical properties, and chemical constituents, and these may have an important bearing on current flow to and from the buried pipes. The character of the street railway roadbed is also an important factor in determining the extent of leakage of stray current into the earth. A well-drained rock or concrete roadbed may in general be expected to offer much higher resistance to the leakage of current than one in which the construction is such that a large amount of moisture is retained. Polarization and film resistances at the surface of the pipes may also be an important factor in current flow. As soon as an electromotive force is applied to a buried pipe the current flow drops off rapidly with time, especially during the first few minutes, due to the setting up of counter e.m.fs. and the formation of film resistances. The extent to which this may occur in some cases is shown in Fig. 10, which shows the effective resistance as a function of time after the application of an e.m.f. of about six volts between two short lengths of cast iron pipe buried about twelve feet apart. From this it will be seen that the initial resistance of about 18 ohms has practically doubled within half an hour after the e.m.f. is applied, and after

that the resistance remains practically constant. In this case the effect of the polarization and film resistance is practically as great as the total soil resistance between the pipes. These results were obtained when the soil was very wet, and it is probable that in a comparatively dry soil the effect would have been less marked.

16. *Resistance of Soils from Different Sources.* In order to give an idea of the order of magnitude of the resistances that may be expected in practise, together with the range of variation of the same, we give herewith a table of resistances of soils taken from various points in the cities of Philadelphia and St. Louis and other cities. In all of these the specific resistance of the soil is measured with the same moisture content which it had when first taken from the ground and all were measured at about one temperature.

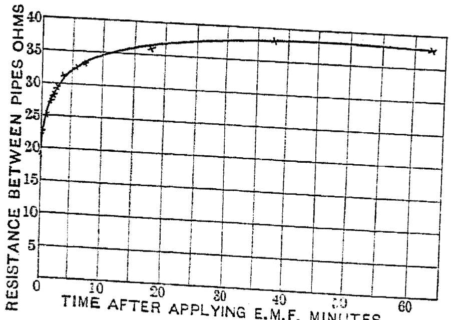


FIG. 10—EFFECT OF POLARIZATION ON RESISTANCE BETWEEN BURIED PIPES

The soils from each city were taken from widely scattered points and represent a wide variety of different kinds of soils, as will be evident from the brief description. The moisture content was determined in each case and is given along with the other data. The results are shown in Table XVI. An examination of this table reveals some striking differences in two particulars: In the first place the specific resistances found in St. Louis shows a much greater degree of uniformity than those found in Philadelphia. The extreme range of values of specific resistance for St. Louis earths is between 400 and 1800 ohms per centimeter cube, while for Philadelphia the range is between 595 and 610,000 ohms per centimeter cube. The other chief point of difference is the magnitude of the mean value of resistance, the average value of the specific resistance for all the samples taken in St. Louis being 1053 ohms, while the average for the Philadelphia

TABLE XVI

SPECIFIC RESISTANCE OF SOILS

No.	Character	Per cent moisture	Ohms per cu. cm. Spec. resistance
	PHILADELPHIA SOILS		
1	Moist gray clay	11.7	651
2	" yellow clay	14.8	3,850
3	" blue clay	16.1	3,036
4	Nearly dry red sand	7.6	2,700
5	Moist red clay	17.4	8,820
6	Nearly dry mica schist	4.7	156,400
7	Nearly dry gray clay	16.2	5,930
8	" " clay, rock and cinders	17.9	595
9	Moist blue clay and gravel	13.1	2,830
10	Moist blue clay	15.3	1,605
11	Moist yellow clay	17.2	5,340
12	Moist yellow clay and sand	13.4	6,280
13	Wet gravel	11.0	24,550
14	Wet humus and clay	9.5	2,600
15	Moist clay, sand, cinders	17.4	2,060
16	Damp, disintegrated schist	12.9	12,100
17	Wet clay, cinders, gravel	16.9	5,000
18	Moist yellow clay	19.4	4,825
19	Moist yellow clay	17.3	3,820
20	Moist red clay	19.3	21,200
21	Moist yellow clay	15.6	25,900
22	" red sand and clay	15.7	13,700
23	" clay, cinders, sand	13.7	1,494
24	" clay and sand	20.0	821
25	Moist clay and sand	18.7	1,774
26	Damp clay and humus	16.7	2,490
27	Damp clay and humus	16.2	2,585
28	Nearly dry disintegrated schist	0.3	610,000
29	Damp yellow clay	16.8	2,250
30	Moist yellow clay	18.5	2,455
31	Saturated clay and cinders	23.8	4,410
32	Moist clay and sand	18.6	6,260
	ST. LOUIS SOILS		
50	Wet clay	20.4	600
51	Blue clay	21.1	700
52	Moist virgin soil	20.8	1,500
53	" yellow clay	21.5	1,250
54	Yellow clay	19.0	1,800
55	Yellow clay		1,600
56	" "	21.1	1,800
57	" "	22.8	1,400
58	Yellow clay	21.3	1,400
59	Virgin black soil	21.2	1,700
60	Yellow clay	16.0	1,800
61	Yellow clay	23.4	990
62	Yellow clay	18.4	700
63	Yellow clay	21.9	950
64	Sand and humus	17.8	925
65	Sand and humus	20.0	900
66	Blue clay	22.0	470
67	Virgin yellow clay	19.1	1,450
68	Virgin yellow clay	22.5	484

TABLE XVI—Continued

SPECIFIC RESISTANCE OF SOILS

No.	Character	Per cent moisture	Ohms per cu. cm. Spec. resistance
69	Yellow clay	22.0	700
70	Virgin yellow clay	20.0	1,700
71	Virgin soil	22.9	840
72	Yellow clay	23.3	900
73	Blue clay	26.1	400
74	Blue clay	19.1	600
75	Blue clay	24.2	830
76	Moist blue clay	23.1	500
77	Nearly dry yellow clay	16.4	1,100
78	Blue clay	17.1	650
79	Yellow and blue clay	26.9	600
80	Yellow and blue clay	19.7	820
81	Blue clay	20.0	750
82	Clay and loam	19.2	1,450
83	Sandy clay	19.5	1,600
84	Yellow clay	22.6	1,200
	PITTSBURGH SOILS		
33	Damp sand	13.4	4,506
34	Moist yellow clay	16.5	2,819
35	Moist clay and humus	20.5	2,300
36	Blue clay	26.5	14,025
37	Moist gray clay	26.3	619
38	Damp sand	13.0	1,335
39	Damp sand	10.2	8,709
40	Loam and cinders	21.8	1,074
41	Nearly dry sand	12.3	2,908
	ERIE SOILS		
42	Moist clay and gravel	6.0	18,080
43	Clay, coal and gravel	16.7	1,796
44	Wet blue clay	19.3	3,779
45	Moist blue clay and sand	11.9	3,080
46	Moist gravel	5.7	14,025
47	Wet blue clay and sand	19.6	2,462
	APOLLO, PA., SOILS		
48		30.5	1,796
	ALBUQUERQUE, N.M., SOILS		
85		15.3	43,960
86		11.1	59,475
87		11.9	41,908
	WASHINGTON, D. C., SOILS		
88	Air dry red clay	4	2,340,000
89	Nearly dry red clay	10	14,660
90	Moist loam	20	8,729
91	Wet yellow clay and sand	30	41,490
92	Wet humus clay and sand	30	24,060

samples was 28,750 ohms per centimeter cube, the latter being over 27.3 times the former. It should be noted however, in making this comparison, that the high average for Philadelphia is due to a large extent to the abnormally high resistance of two samples containing large quantities of mica, one of which had a specific resistance of 156,400 ohms and the other 610,000 ohms. If these two are eliminated the remaining 31 specimens show an average for Philadelphia of 5885 ohms per centimeter cube, which, however, is still over 5.6 times the value for St. Louis. It is quite probable that this difference is such as to prove an important factor in the electrolysis situation in the two places.

CONCLUSIONS

The following are some of the more general conclusions that may be drawn from the experimental data presented in this paper:

1. The current density has a marked effect on efficiency of corrosion of iron in soils, the efficiency of corrosion being in general greater, the lower the current density. In saturated soils the corrosion may vary between 20 per cent and about 140 per cent for the range of current densities between 5 milliamperes and 0.05 milliampere per square centimeter.

2. Moisture content in the soil also has a marked effect on efficiency of corrosion, the corrosion efficiency being in general greater with increasing moisture content, up to saturation of the soil. Beyond this point increased moisture content has comparatively little effect.

3. Temperature changes within the limits commonly met with in practise have no important effect on corrosion efficiency.

4. The depth of burial of pipes has no direct effect on corrosion efficiency, provided other conditions remain constant. In practise, however, the moisture content, current carried by the pipes, and various other factors which affect corrosion efficiency will vary with depth, so that indirectly differences due to depth may be noted.

5. The amount of oxygen present has no appreciable effect on the efficiency of corrosion, in the case of iron immersed in liquid electrolyte.

6. Corrosion efficiency of iron imbedded in earth is always greater in open vessels than in sealed vessels.

7. The amount of oxygen present has a marked effect on the end products of corrosion. If the corrosion is rapid and the supply of oxygen small, there will be a preponderance of magnetic

oxide, while if the rate of corrosion is low and the supply of oxygen abundant the ferric oxide will predominate. Owing to the fact that the supply of oxygen around pipes buried in earth is always more or less limited, the character of the oxides formed gives some indication as to the rate of corrosion, and thus indirectly as to the cause of the corrosion, if local conditions are properly considered.

8. There is no material difference in the efficiency of corrosion shown by the various kinds of iron commonly used in the manufacture of underground pipes.

9. The fact that a given chemical tends strongly to inhibit either self-corrosion or electrolytic corrosion in liquids is no indication that it will materially retard electrolysis of iron imbedded in soils.

10. Pitting of iron imbedded in soils is affected not only by a non-homogeneous condition of the iron or soil, but also by the chemicals contained in the soil.

11. The efficiency of corrosion was found not to be a function of the voltage except in so far as the current density may be affected. Voltages as low as 0.1 and 0.6 volts showed practically the same efficiency of corrosion as 5 to 10 volts or higher.

12. Corrosion tests on a large number of different kinds of soil from widely different sources, with average moisture content and moderate current density, indicate that corrosion efficiencies between 50 and 110 per cent may usually be expected under most practical conditions.

13. The resistance of soils varies throughout a very wide range with variations in moisture content, the resistance of the comparatively dry soil being of the order of several hundred times the resistance of the same soil at about saturation. Above saturation, increase in moisture content has but little effect on the resistance of the soil.

14. Because of the great variations in resistance of earth with moisture content, voltage surveys should not be made at times when the earth is extremely dry.

15. The resistance of the soils varies greatly with temperature within the ordinary range encountered in practise. In the case of the soils tested, the resistance at 18 deg. below zero cent. was over two hundred times as great as at 18 deg. above zero cent. Even at about freezing temperature the resistance will be several times that at summer temperatures. This not only has an important bearing on the magnitude of the electrolysis

trouble that may occur at different seasons, but it also indicates that, where practicable, voltage surveys should not be made when extremely low temperatures prevail.

16. The experimental results given in this paper have an important bearing on the subject of electrolysis mitigation through the limitation of voltage drop in the negative return. For some years the chief means of preventing trouble from electrolysis in certain foreign countries has been the limitation of the permissible voltage drop between any two points on the return circuit. In some places the limit has been placed on the maximum voltage during peak load, whereas in other cases the average voltage for twenty-four hours has been the determining factor. It will be evident that if the total amount of damage which results is proportional to the average current, then the limitation of the average voltage would be more logical than the limitation of the peak load voltage, since in the former case the cost of meeting the voltage limitation in any given case would be proportionate to the danger involved irrespective of the station load factor; whereas if the voltage at peak load is the determining factor, the cost of complying with the requirements depends not only on the danger involved, but on the load factor of the system, and the poorer the load factor, the greater its cost will be. It appears from the data presented in this paper that the rate of damage does not increase as fast as the voltage increases, because of the tendency toward lower corrosion efficiencies at higher current densities. This indicates that, with a given average all-day current, the actual amount of electrolysis that would occur would be less with a bad load factor than with a good load factor, and hence points to the undesirability of penalizing a high peak of short duration. It would appear very much more logical, therefore, in so far as the damage itself is concerned, to make the average all-day voltage the basis of the limitation, rather than the voltage at time of peak load.

In conclusion, the authors wish to acknowledge their obligation to their colleagues, Mr. O. S. Peters and Dr. H. E. Palmer; to the former for valuable cooperation in the development of the electrolytic method for cleaning anodes which was used throughout this investigation, and also for a large amount of work on the measurement of earth resistances; to the latter for the chemical analyses of soils, and the carrying out of experiments on the effect of oxygen on the end products of corrosion.

DISCUSSION ON "ELECTROLYTIC CORROSION OF IRON IN SOILS" (MCCOLLUM AND LOGAN), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

J. L. R. Hayden: The paper on electrolytic corrosion by Messrs. McCollum and Logan is very interesting for the large amount of data it gives on electrolytic corrosion under actual service conditions, that is, with the iron imbedded in the soil.

The observation that the activity decreases with increasing current density I found very marked in my investigation. I found that under conditions where passivity is possible, complete passivity could be produced by raising the current density, even if only momentarily. Limited time did not allow me to investigate to any great extent the electrolytic corrosion when the circulation of the electrolyte was interfered with by soil or sand, but some experiments showed the same phenomenon observed by the authors, that the "passivating" action is materially decreased by interference with the circulation of the electrolyte. If the passivity is due to the electrolyte in which free hydrogen ions cannot exist, as has been suggested, this phenomenon would easily be explained.

Alexander Maxwell (communicated): We are indebted to Messrs. McCollum and Logan for their excellent paper. The work is noteworthy, not only on account of the range and scope of the data presented, but especially because it is in great measure directly useful, and applicable in connection with field work.

A most important feature of these tests is in the relation between the current density and "efficiency of corrosion." As noted in the paper, the results reported by Ganz in 1912 showed, in general, higher "efficiencies of corrosion" than those found by Messrs. McCollum and Logan; and in the former test the current densities employed were much lower than those used by the authors of the present paper.

The authors have used current densities ranging from 0.03 to 5 milliamperes per square centimeter. It may be interesting to compare these densities with some observed by the writer under actual conditions in city streets.

The following values are calculated from a large number of tests made with Haber's "earth ammeter." These tests were all made in connection with pipes which had actually suffered severe damage by corrosion, and most of the tests were made in places where the current density might be expected to be high, as where only a few feet of soil intervened between the pipe and the rail, and when the pipe was definitely and strongly positive to the rail.

Under these circumstances, it was found that the average apparent current density for areas between 100 and 600 square centimeters, varied from 0.0005 to 0.04 milliamperes per square centimeter. While these measurements were not of great accuracy, I believe that they are dependable as indicating the

general order of magnitude of currents leaving pipe surfaces under the conditions noted above.

It would be interesting to extend the investigation of the variation in corrosion efficiency to very low densities such as those indicated above, for I believe that such densities are more nearly representative of average field conditions, and all of the evidence points towards corrosion considerably in excess of theoretical values, at these low densities.

D. C. Jackson: The authors have brought out in this interesting and useful paper many things that have been previously known, or at any rate supposed to exist, but they have been brought out more clearly in some ways in this paper than heretofore; and they have added materially to the available information on this complex subject. A paper of this kind is one we can wisely listen to, as the electrical enterprises have been too prone to overlook the economic importance of consideration for their neighbors.

Let us see what it means in certain industries if stray-current electrolysis is allowed to proceed. I will for illustration take an art aside from electrical engineering. Take gas, for instance, and consider the case of a gas plant that has an output of 200 million cubic feet per annum. That would be a sufficient gas supply for the needs of a city from 30,000 to 50,000 inhabitants. Suppose the leakage from the mains is doubled from the fairly normal rate of 5 per cent up to 10 per cent, due to the fact that the pipes are fairly rapidly corroded or the joints are affected and it is difficult to keep the pipes tight. Illuminating gas is worth in the Eastern States, delivered at the outlet to the holders, approximately 30 cents a thousand cubic feet, which makes the extra leakage due to electrolysis cost $3000 per year. It costs the company that much to generate and put in the holder the gas lost from the mains on account of their deteriorated condition. Capitalizing that means a good deal of money, in addition to the other various disadvantages that arise from leaky gas mains; and that is for gas mains alone, and leaves out other underground structures. It also makes no allowance for the extra cost of repairs to the mains, which is necessary on account of their leaky character.

If, instead of a little city, in which 200 million cubic feet of gas are sold, we take a large city with a sale of 5000 million cubic feet of gas, under similar conditions of doubling the leakage from 5 per cent to 10 per cent, on account of the corroded mains, and we consider that the gas costs the company at the outlet of the holder 30 cents a thousand, the increased loss of gas becomes a matter of $75,000 a year.

That illustration shows very clearly the problem which Mr. McCollum has been working on, which is of considerable importance. The question is really an economic one. It relates to the expenditure that might be made for protection of underground structures from the ravages of electric railway currents

and the balancing of the annual cost of protection against the annual cost of the injury that the stray currents produce.

Hugh T. Wreaks: I notice that all of the experiments were made on uncoated pipe, and I am curious to know whether future experiments would take in the line of coated pipes, that is, enameled, sherardized or galvanized, because in a recent lecture I attended over in Brooklyn, one of the city engineers described the preparation of their water pipes so as to resist corrosion, and laid great stress on the value of enameled coating; this coating being covered by fairly definite specifications on ductility, strength, melting temperature, etc.

If this has not been touched upon in other papers, I believe it is germane in this discussion.

Harold V. Bozell: Prof. Jackson's mention of gas mains calls to mind a practise in Oklahoma, where usually gas and electric interests in one town are under one ownership and there is mutual interest in looking for solution of the electrolytic problem. I don't know how this has worked in the East, if it has been used, but it was found there that by running gas mains on both sides of the street much less electrolysis resulted; of course the greatest electrolysis occurs in the cross pipes and this was eliminated. It should be stated that paving, access to pipes and other items added to cause the double main system.

Harry Barker: I would like to ask if the soil studies at the Bureau of Standards were carried into alternating-current work. Question continues to arise generally as to the electrolytic effect of alternating current. We would expect of course that where the reversal of the current is rapid, there is little time for secondary chemical reactions to intervene; then on the reversal of the current the original electrochemical reaction itself is reversed. Where the time involved is considerable, the secondary changes may prevent complete reversal. Some experimental results confirming this are available but a wider range is still desirable.

I presume, from the completeness with which the Bureau of Standards has undertaken its corrosion studies, that they must have well considered such points. But the Bureau has said comparatively little about its alternating-current work and, if it would not be publishing the results too early, perhaps Mr. McCollum might add a word on it.

F. C. Caldwell: With regard to the last point in the paper, that is, the limitation of the voltage, I would ask if it is true that it is not wise for a municipality to set a limit to the voltage to be permitted in the tracks, because of the fact that if they do so they are liable to relieve the railway company from responsibility in the matter. That is, if the railway company complies with the requirements of the municipality and keeps its voltage within the prescribed limit, the fact that such limit has been prescribed relieves the railway company from any further responsibility for electrolysis which may take place within that limit.

J. C. Lincoln: I inquire if the authors have any information as to the effect of breaking the pipes, that is, breaking the electrical continuity of the pipes, in lengths of a few hundred feet, or several thousand feet—whether they have any information as to what the effect of such breaking is on the electrolytic effect?

Henry G. Stott: I want to say one word as to the question of the responsibility of the railroad companies, which has been brought up. I would like to remind the gentlemen present that there was a very able paper presented before the Institute some three or four years ago by Mr. George I. Rhodes, which treats this subject very fully, and I think that paper was really a classic on the question of electrolysis, and upon its cure, which is more important. Broadly speaking, the voltage drop in the return circuit has very little to do with the amount of damage, that is my experience. It is more a question of where you lead the current back. By insulating the negative return to the substation or power station, as the case may be, by this method it is possible almost entirely to prevent the leakage of current from the rails to surrounding conducting bodies, and that is the method which the companies with which I am connected have adopted most successfully in some very trying cases.

I simply wish to remind the members who are interested in that subject of the paper written by Mr. Rhodes, as it was one of the clearest expositions on the subject ever presented to the Institute.

Albert F. Ganz: The paper is full of valuable results and conclusions. It describes a very large number of tests made in a laboratory with the accuracy obtainable only in a laboratory, and yet made under conditions exactly resembling those found in every-day practise. Perhaps the most important single result reported is that electrolytic corrosion of iron in ordinary soil, with the low current densities usually met with in practise, follows Faraday's law. This means that under the usual practical conditions met with in electrolytic corrosion of underground iron structures, we can compute the weight of iron corroded on the basis of approximately 20 pounds of iron per ampere-year.

The authors have shown that corrosion efficiency varies with current density, and that with current densities of an order greater than a few milliamperes per square centimeter the corrosion efficiency decreased from 100 per cent to low values with increasing current density. For very low current densities, of the order of a few hundredths of one milliampere per centimeter, they have generally obtained corrosion efficiencies somewhat larger than 100 per cent.

They state that they have not been able to obtain the high efficiencies of corrosion, up to 500 per cent, which I found in some of my tests reported last year. I wish to say in explanation that these high efficiencies of corrosion were obtained only in the tests where the surface scale had not previously been removed

from the test pipe, and where the pipes had only been cleaned to remove dirt and grease. In the tests which I made where the pipes were first turned down in a lathe, removing all surface scale, I obtained efficiencies of corrosion varying between 103 per cent and 123 per cent, which values agree well with those found by the present authors. The very high values found by me were therefore due to the effects of the surface scale.

During the past year I have made a few tests for efficiency of corrosion with soils obtained from several cities, using low current densities of less than one milliampere per square centimeter, with iron anodes cleaned of scale, and I have found values generally somewhat above 100 per cent.

It may be of interest to compute the probable density of current leaving iron pipes in ground and returning to trolley tracks under assumed practical conditions. The resistivity of soil given in the paper varies between 400 and 6000 ohms in a centimeter cube. Assuming a distance of three feet (91 cm.) between a pipe and the rails to which the pipe is positive in potential, the resistance of an intervening column of soil one square centimeter in cross-section would vary between 36,000 and 540,000 ohms. With one volt potential difference there would result a current of from 0.03 to 0.002 milliampere through the column of soil; this corresponds, therefore, to the average density of the current leaving the pipe surface under the assumed conditions for one volt of potential difference. With 5 volts potential difference, a value commonly found in practise, the resultant average current density would vary from 0.15 to 0.010 milliampere per square centimeter.

As to the values of current density which may be considered dangerous to an underground pipe, it should be remembered that in nearly all practical cases of destruction by electrolysis from stray electric currents, localized pits are produced, which shows that the current generally leaves from localized areas. It is pointed out in the paper that a current density of 0.05 milliampere per square centimeter would cause corrosion to proceed at the rate of one centimeter in seventeen years; this is equivalent to approximately $\frac{1}{8}$ in. (0.32 cm.) in five years; current leaving a steel or wrought iron pipe with a $\frac{1}{8}$-in. (0.32 cm.) wall, of a density of 0.05 milliamperes per square centimeter, would pit entirely through the metal in five years, provided that the current left the pipe surface uniformly and corroded the pipe uniformly. If, however, the current should leave from 10 per cent of the pipe surface, this same average current density of 0.05 milliamperes per square centimeter would corrode through the metal of the pipe in one half-year, and a current density of only 0.005 milliampere per square centimeter, leaving from 10 per cent of the pipe surface, would pit through the pipe in five years. This very low current density would therefore be dangerous to the pipe.

Regarding the effect of moisture, the authors have found that

as soils are dried the corrosion efficiency is decreased. They suggest that this may be due to the fact that with dry soil the iron is in less uniform contact with the soil, so that the current discharged from localized areas results in higher current density of discharge at these points. This is the logical and probable explanation. I do not believe, however, that this in itself gives much promise of diminished danger to pipes from electrolysis, because while the total amount of corrosion may be less, this may be so concentrated as to be quite as effective in producing pits through the metal of the pipe.

Professor Caldwell has stated that in his opinion it would be undesirable for a municipality to limit the voltage drop in rails by an ordinance, because this would stop them from obtaining damages from electrolysis so long as the terms of the ordinance are complied with. In reply to this statement I would like to say that legal authorities have advised me that the enactment and enforcement of a city ordinance does not take away from a municipality or from the public the common law right to sue for and obtain damages that may be caused by stray electric currents even if the terms of a special ordinance, designed to minimize such dangers, are complied with. The reason is that the common law is superior to a city ordinance.

Burton McCollum: In regard to the point brought up by Mr. Hayden's written communication on the passivity of iron, it would be out of the question here to enter into a discussion of the cause of passivity in iron. It is a matter which has been investigated a great deal, and has led to a great deal of controversy, but I do not agree with Mr. Hayden that passivity is found only when the iron is in an electrolyte in which hydrogen ionization cannot exist—that is, in an alkaline electrolyte.

We are all familiar with the fact that iron is passive in any strong alkaline solution, but we also know that iron can be rendered passive and remain passive in very strong acids. As a matter of fact, there is a great deal of evidence accumulated to show that there are probably a number of different causes of passivity, in addition to those that occur in an alkaline solution.

As to some of the points brought up by Prof. Jackson; he speaks of the effects of moisture on the efficiency of corrosion and on resistance, and seems to be inclined to attribute most of the lack of electrolysis in dry soils to the high resistance. I think, probably, that that is the case, but it might be pointed out that the tendency of the low efficiency of corrosion is to produce the same result as that which would be caused by the reduction of current by the high resistance, so that these causes are superposed, and it is difficult to say how much reduction in corrosion may be due to one and how much due to the other. Probably the resistance is the most important factor.

As regards concrete roadbed, I think it will as a rule give a higher resistance than a dirt roadbed, in which the rails are pretty well buried in the soil. I have made tests of the specific

resistance of water-soaked concrete at the Bureau of Standards, and find that it ranges from 5000 to 8000 ohms per centimeter cube, which is very much higher than the resistance of many earths, but perhaps not much higher than the average of all. The superiority of concrete roadbed is great only where earth resistances are low, but in many cases I think it will greatly reduce leakage currents.

The question was raised as to whether Faraday's law always holds. In order to answer that it is necessary to say just what we mean by Faraday's law. As Faraday's law was originally stated, it applies to the decomposition of the electrolyte. In modern electrochemical processes, we think of it as applying to all reactions which take place at the electrodes. When we think of it in that sense, Faraday's law always holds. If an iron anode is corroded at 100 per cent efficiency, then one gram equivalent of iron will be corroded by the passage of 96,540 coulombs of electricity, and Faraday's law holds true as applied to corrosion of the anode. If, however, the iron is in a solution which renders it passive, there will be no corrosion of the iron, and in that case the electrolyte breaks up in accordance with Faraday's law, and 96,540 coulombs of electricity will result in the breaking up of one gram equivalent of electrolyte.

If, for instance, an iron anode corrodes at 60 per cent efficiency, then 0.6 of a gram equivalent of iron will be corroded by 96,540 coulombs of electricity, and at the same time 0.4 of a gram equivalent of the electrolyte will be broken up, so that Faraday's law still holds when we consider all of the reactions which take place at the anode.

As to the relative amount of current in pipes in warm and cold weather, it would appear that if the depth of rail is not more than 9 inches and if the earth is frozen to a greater depth than this throughout the entire system, the amount of leakage from the track is bound to be much less than it would be in case there were no frost in the ground, and that would lead me to believe that the current flowing in the pipe under those conditions would be considerably less than if the ground were not frozen.

I want to endorse highly the statement made by Prof. Jackson in regard to the matter of balance between the actual damage and the cost of protection. It is neither necessary nor desirable to eliminate entirely all electrolytic trouble, but the desirable thing is to reduce the loss to such a value that any further reduction of loss would be more expensive than to repair the loss.

Mr. Wreaks brought out the question of coated pipes. We now have in course of preparation a report dealing with the subject of corrosion of coated pipes. I may anticipate the results to the extent of saying that of a very great number of commercial pipe coatings which we have tested we found very few which we considered to be of any value. In fact, they are rather detrimental, because they tend to concentrate the corrosion. There

are some coatings, however, such as extremely heavy layers of pitch, which may give protection for a considerable time, but it is doubtful whether the protection thus secured is worth the cost. Besides, such treatment is merely symptomatic and does not get at the cause of the trouble, and for that reason surface insulation, if used at all, should be supplementary to means applied to the tracks for reducing leakage of stray currents from the rails.

As to enamel coatings for protecting pipes, I think that is a question as to whether they have suitable mechanical properties, and it is also a question of whether they are waterproof. If they are absolutely and permanently waterproof, they will remain insulating and protect the pipes, but if they develop slight flaws and permit the least trace of moisture to soak through and come in contact with the pipes, local corrosion and pitting will occur.

Mr. Bozell brought up the point of placing the pipes on both sides of the street. That is a good thing to do, and it is done a good deal in many places at present. I am confident, however, that that is not sufficient in itself to reduce electrolytic troubles to a satisfactory minimum unless something is done in the way of providing a proper negative return for the current. Besides, we have the problem of protecting pipes already in place as well as those to be laid in future.

Mr. Barker brought up the subject of alternating-current electrolysis. A good deal has already been published on that subject, and among others I may mention a paper by Mr. S. M. Kintner, published several years ago, in the *Electric Journal*, in which he gave the results of some experiments which he carried on with alternating current under practical conditions, and found the corrosion was but a fraction of a per cent of the amount of corrosion caused by direct current. Our own experiments have verified these results, and I do not believe that electrolysis from alternating currents is likely to become a serious problem, except in very special cases.

As to the matter of limitation of the voltages, and such limitation relieving the railway companies of responsibility, as suggested by Mr. Caldwell, I would not approve of any specific limitation of voltage that would relieve the railway companies of responsibility, unless it had been absolutely proved that such limitation was sufficient to relieve electrolysis troubles in a satisfactory manner. Until further data on this point are secured, I do not think it is wise to enter into any agreement that will relieve the railway companies of responsibility for the damage.

The subject of resistance joints in pipes was brought up, but as this subject is being treated at length in a report of the Bureau of Standards, which is now in preparation, I will not attempt to discuss the matter here, other than to say that if properly applied it may have some value as a secondary means of electrolysis mitigation, but the difficulty with it is that if the

resistance joints are not inserted with sufficient frequency there will be such a large drop across the joint as to injure the joint itself, and unless it is accompanied by some primary means of mitigation, in which the potential gradients in the earth are reduced to a low value, it is likely to become very expensive.

I think the subject brought up by Mr. Stott, that of using insulated negative return feeders, is deserving of the most careful consideration. We have given much study to this method of reducing leakage of stray currents into the earth. I am convinced that when properly applied it offers one of the most effective and economical means of attacking the electrolysis problem. This subject is being treated at length in a publication which the Bureau of Standards is preparing to issue shortly, dealing with the subject of Electrolysis Mitigation.

As to the question of current density brought up by Mr. Maxwell, and again by Prof. Ganz, I might point out that the very low current density which he referred to, say 0.005 of a milliampere per square centimeter, if uniformly distributed could not produce any serious damage. Such a current uniformly distributed, even if 100 per cent corrosion efficiency be assumed, would not produce any serious corrosion in less than 100 years. However, the method of measuring the current was such that they measured average current, and undoubtedly the actual density of current discharge was greater than that, and that was responsible for the corrosion which resulted, unless there was a good deal of soil corrosion also. I think, therefore, that the current densities used in these experiments will pretty nearly include the limits within which damage may become serious in practise, though perhaps they should be extended a little further on the lower side, in accordance with the calculation of Prof. Ganz. By current density, we mean not average current density, but the current density at the point where the current is going off the pipes or where pitting takes place.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

THE NATIONAL ASSOCIATION OF CORPORATION SCHOOLS

BY F. C. HENDERSCHOTT

The idea of a national association of corporations maintaining or desiring to establish educational courses for their employees grew out of the experience of the New York Edison Company's commercial school. This company has for some years conducted free technical courses out of working hours at which attendance was optional, but the business-getting end of the industry had received little attention. In organizing a school for its salesmen the company found an enormous task on its hands. Being desirous of having the best salesmen possible, it was willing to spend large sums to perfect educational courses. A thorough canvass of existing practise in training employees for effective service was made and many corporation schools were visited. On the basis of these studies an educational system, involving lectures by experts and examinations based thereon, was inaugurated, and proved successful from the start.

The difficulty experienced by the Edison Company in securing data on corporation schools suggested the possibilities of an association that would act as a clearing house for corporations which, seeing the advantages to be gained by educating their employees, wish to start schools. Such an association should be of great assistance in improving and enlarging courses already started and increasing the efficiency of administration of these courses. A few experts were consulted by the officer of the company having charge of the new school work and a temporary organization was effected. The industries were canvassed to determine how such an association would be received and the response from many was encouraging. On January 24, 1913, a

convention was held at New York University, at which a constitution was adopted, officers were elected and provision made for the appointment of working committees. There were present at this convention representatives of thirty-seven corporations, all keenly interested, all desirous of allying their companies with the new organization. In a report issued by the temporary organization this statement was made:

"The purposes of the association, in brief, are to render new corporation schools successful from the start by warning them against the pitfalls into which others have fallen, and to provide a forum where corporation school officers may interchange experiences and so improve the instruction in their respective schools. The control is to be vested entirely in the member corporations, thus admitting only so much of theory and extraneous activities as the corporations themselves feel will be beneficial and will return dividends on their investment in time and membership fees."

The report suggested the necessity for the appointment of committees on instructors, on allied institutions, and on education. It contained also the following recommendations:

"1. It would seem to be a serious error for the association to attempt to formulate courses.

"2. The association does not propose to institute correspondence courses, since such activity would be far removed from the purposes of the association.

"3. The association recognizes that each corporation has its special requirements. It will be its object to aid the individual corporation in perfecting courses which best fit its needs."

The following articles from the constitution are worthy of quotation, since they show the plan of membership and the emphasis placed on the corporation as the controlling factor.

"ARTICLE III—MEMBERSHIP"

"Section 1. Members shall be divided into three classes: Class A (Company Members), Class B (Members), Class C (Associate Members).

"Section 2. Class A members shall be commercial, industrial, transportation or governmental organizations, whether under corporation, firm or individual ownership, which now are or may be interested in the education of their employees. They shall be entitled, through their properly accredited representatives, to attend all meetings of the Association, to vote and to hold office.

"Section 3. Class B members shall be officers, managers or instructors of schools conducted by corporations who are Class A members. They shall be entitled to hold office and to attend all general meetings of the Association.

"Section 4. Class C members shall be those not eligible for membership in Class A or Class B who are in sympathy with the objects of the Association. They shall be entitled to attend all general meetings of the Association."

"Article VII—Dues"

"Section 1. The annual dues of Class A members shall be $50.

"Section 2. The annual dues of Class B members shall be $5 and the annual dues of Class C members shall be $10."

The first meeting of the executive committee was held on April 4. From the reports presented it was apparent that the movement is bound to interest a large proportion of the 200 or more corporations now conducting educational work. The reports showed also that data on the educational courses of industrial concerns all over the country are being collected and classified by the educational committee.

Already the movement has corporations representing a capitalization in excess of three billion dollars, and employing over 500,000 employees.

The following is the list of Class A charter members:—American Locomotive Company, New York, N.Y.; Brighton Mills, Passaic, N. J.; Brooklyn Union Gas Company, Brooklyn, N.Y.; Burroughs Adding Machine Company, Detroit, Mich.; Cadillac Motor Car Company, Detroit, Mich.; Carnegie Steel Company, Pittsburgh, Pa.; Commonwealth Edison Company, Chicago, Ill.; Consolidated Gas Company of New York, N. Y.; Curtis Publishing Company, Philadelphia, Pa.; Dodge Manufacturing Company, Mishawaka, Ind.; Henry L. Doherty and Company, New York, N. Y.; R. R. Donnelley and Sons Company, Chicago, Ill.; Thomas A. Edison, Inc., Orange, N. J.; General Electric Company, Schenectady, N. Y.; Haines, Jones and Cadbury Company, Philadelphia, Pa.; Larkin Company, Buffalo, N. Y.; National Cash Register Company, Dayton, O.; New York Edison Company, New York, N. Y.; Norton Company, Worcester, Mass.; Packard Motor Car Company, Detroit, Mich.; Pennsylvania Railroad Company, Altoona, Pa.; Public Service Corporation of New Jersey, Newark, N. J.; M. Rumely Com-

pany, LaPorte, Ind.; Spencer Trask and Company, New York, N. Y.; Spirella Company, Meadville, Pa.; Trow Directory Printing and Bookbinding Company, New York, N. Y.; Travelers Insurance Company, Hartford, Conn.; Western Electric Company, Chicago, Ill.; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; Yale and Towne Manufacturing Company, Stamford, Conn.

On September 16–19 the first national convention of the association will be held in Dayton, Ohio, under the auspices of the National Cash Register Company. Working plans for the coming year will be adopted.

The field of activity opening for this body is unlimited. Corporations are fast being converted to the theory of training their own men. They no longer expect to find satisfactory help ready-made, but are now applying themselves to the task of making men as well as commodities. The universities and colleges, too, are seeing in this new movement a link, long sought, between our institutions of learning and the business world, and are anxious to affiliate and push forward this new educational system.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

VOCATIONAL EDUCATION IN PHILADELPHIA AND VICINITY

BY A. J. ROWLAND

Vocational Education is a term which has so wide a scope that in the following brief report certain limitations will be established which will, it is hoped, tend to give a larger value to the statements made in it. The first limitation is to consider only those kinds of vocational education which would be certain to be of direct interest to members of the American Institute of Electrical Engineers. Having some doubt as to how much vocational and professional education overlap, and realizing that the general character and purpose of regular engineering courses, and, for that matter, of manual training and trade school courses, are quite well understood, the writer has decided further to limit the scope of his section of this report to information regarding education offered and made available to men whose employment is in or closely related to engineering industries. He does this with a certain amount of regret, believing there are points of interest and matters worthy of discussion which might be noted in regard to various institutions in the vicinity of Philadelphia which cannot be referred to. Among other things he has in mind the engineering courses at Drexel Institute, which have been operated with increasing success for many years, although nothing has ever been put into print regarding them, except that which appears in the regular printed circular. They are laid along lines somewhat different from those found in university courses on the one hand, and are quite different from courses in trade or industrial schools on the other. Those who operate them believe they fill a distinct place in engineering education and have

a merit that has not been widely recognized mainly because no publicity at all has been sought for them.

Having defined the particular field of this section of the report, most of what is stated hereafter relates to evening class instruction; since the man who is to have technical training in this vicinity must in nearly all cases obtain it " after hours."

General Conditions in Evening Education

In Philadelphia the educational opportunities offered to workers are not copied from plans worked out elsewhere, which are now on trial here. In every case the classes have been formed to meet some definite need which has been felt. Out of this very condition of affairs has arisen a process of development in each institution, all its own, made with little or no regard to what others have done or may have found desirable. At the present time, however, a strong feeling has arisen that considerable improvement could be made by securing a mutual understanding of plans of courses and purposes of the institutions giving them. There is certainly strong indication, also, that employers as well as employees are waking up to the commercial value of technical education. Through better understanding of each other and by hearty co-operation between schools and large employers, there is every reason to believe that the future of vocational education is to be worked out in ways which will be for the good of the city.

Evening Class Problems

Evening class work in Philadelphia presents certain problems which are, no doubt, the same as those encountered everywhere; but a statement of them here will help to make clearer the particular kinds and arrangements of class work mentioned later.

Many men wish to be given instruction at once and only in the particular branch of knowledge in which they feel a need; they are impatient of preparation in mathematics or science or any other subject. Thus a man may never have gone beyond those branches included in primary school education, but he wants instruction in alternating currents and cannot understand why he cannot be immediately taught as much of this subject as anyone else knows. Standard systems of education as used in day schools will not meet the requirements.

Those who seek evening class work are often short-sighted in considering the kind of training which they need. Thus a man nployed in the Department of Public Works may seek a course

on "the laws regarding garbage removal," seemingly unconscious that for his real advancement he should have instruction in sanitary engineering. Or another man wants to study "telephones," not realizing that, could he get the opinion of the head of his department, he would find that for real progress in telephone engineering he must have a broad knowledge of physical science and in particular a thorough comprehension of electrical principles and applications.

The same narrow view of what they need makes it difficult to get students to pay attention to a proper use of the English language; to be careful of penmanship and spelling; to be neat in arranging data; or to have any care except to get certain particular knowledge of technical subjects. They are likely to have no thought of developing their mental powers or of widening their outlook either for the practical purpose of increasing their opportunities in life, or of securing education merely for its own sake.

Many a man finds that tuition charges, even though they are very small, along with expenses for books, carfares, and perhaps for clothes, to maintain a creditable appearance before his classmates, make a bar so absolute that evening class work is impossible, no matter how much he would like to take it. This is particularly true of more mature men with family responsibilities, great numbers of whom feel their very great need and yet realize the hopelessness of satisfying it.

Other difficulties might easily be presented: there is the short time available for teaching a given subject; the fact that, coming at the end of the day, men are tired and ready for rest; that often long distances must be traversed to reach desired classes.

Methods Used to Meet the Problems

In connection with the descriptions of classes and courses later, it will be found that various definite methods are used to meet the problems just stated. In some places students are accepted for engineering training, no matter how limited their knowledge. The instruction is then put on a very elementary basis and the student gets what he can. Every technical subject can be explained to some extent without demanding of the student a preliminary knowledge of mathematics or science. Much good work is done this way, especially for those whose interest is slight, or whose mental powers would not respond to any such training as commonly precedes the study of engineering subjects.

Some classes are at the other extreme. Definite entrance requirements are set and the subjects are given on the same basis as regular college instruction.

Most institutions arrange *among their own courses* to so fit things together that the education of a given year may lead on to other things or the work of a single class be widened out into a whole set of subjects, thus providing a way to lead men on without loss of time as their views change and they come to understand the breadth and bearing of the topics they have begun to study.

Difficulties of many other sorts are met by plans which need not be described in detail. A short time to cover a big subject puts both teacher and students on their mettle; no time can be lost; every topic undertaken must have a definite aim. Unless each evening the student feels that the loss due to staying away is so great that he cannot afford it, something is wrong with the subject or the instructor. One of the advantages of evening class education is that the class has a definite goal and must make definite progress toward it every time it meets.

The difficulty of the classes being *evening* classes is much overestimated. Everyone who has passed the regular "going to school" period in his life does much of his studying evenings; they must be used if one hopes to keep up to the times. The stimulus of a class at work; of an enthusiastic teacher; the possibility of learning by the mistakes of others as well as by one's own; the possibility of direct explanation of difficult points; the embarrassment of being called on for something one has not looked up—all lead to the certainty that far more can be gained by class work than by sitting quietly by the library lamp at home with the best book on the subject in hand. Sleepy and dull students in an evening class usually reveal a dull, unresourceful, or incompetent teacher.

The financial problem of the evening student is one of the hardest to solve. Experience shows that free classes are not successful. Few people value that which costs them nothing. Most institutions conducting evening classes do not expect the receipts from tuition to come anywhere near to paying the cost of instruction. The tuition fee is commonly so low that it is frequently a small part of the total expense. The writer knows of cases in which the railroad fares, alone, of students attending his classes were five or six times the cost of tuition. By keeping the expense at the lowest possible figure, it is certain that many ought to be reached

who simply cannot afford to pay the bills. As far as the writer knows, there has been no firm in Philadelphia as yet that has made arrangements to offer to help its employees in this matter. This is one point where it would be pleasant to see the practise in some other cities adopted.

Possibilities in Evening Education

The possibilities in evening education are hardly realized by most people. It is only those who know how evening students work, and the way they push on, who can appreciate how much they can absorb in a limited time if the work is carefully laid out. It sometimes seems as though the very fact that their attention in school work is focussed wholly on one or two subjects enables them to grasp new things and understand difficult matters in an unusual way. In a majority of cases students who seek vocational training in evening classes are already employed in work of a definite character in which they see prospects of advancement. They know what kind of knowledge they want and what they are going to do with what they get. They see at once the practical bearing of theoretical principles and have a point of view quite different from that of most students—even college men.

It is a pity that the miscellaneous character of evening courses which are offered, and the diversity of entrance requirements, lead to misunderstanding in many cases as to what those who finish them really know. While very elementary work is done in subjects commonly considered the heavier and more theoretical in engineering work, there are, at the other extreme, courses for which exacting entrance requirements are set, in which, in character and scope, the training is equal to that given seniors in college.

Exclude shop courses and the like for rather obvious reasons, and the writer believes that if a *comprehensive* plan of dealing with this matter of kind of courses and entrance requirements were possible, men could be properly classed by considering their previous knowledge and started on courses of training which could be indefinitely continued; while the student would be sure of direct value from what he had taken, no matter at what point he chose to interrupt his course. At present a man starting upon a vocational course is likely a little later on to find that he has reached a point in education from which he can make no direct advancement. If he enters a trade course, some bar in

mathematics or science will prevent his going on with advanced work. The knowledge he already has in the line which interests him must be dropped and a new start be made. A man who has done well in a trade course in plumbing cannot enter a class in sanitary engineering even though he knows much more about practical problems in the subject than many men who have a different preparation. The pity of it is that there are always a few men who take courses of a simple kind, the best in their classes, who should be encouraged to go further. Such conditions are especially bad when a change from one institution to another must be made.

If such a comprehensive plan were possible, the applicants would be divided into four grades:

1. Men who have completed technical high school courses; who are therefore ready by educational preparation and by mental ability to enter immediately college grade work, which would be provided for them.

2. Younger men and boys who have completed or nearly completed grammar school training. They may be given work of high school character selected so that they shall receive, in as brief time as possible, training in subjects making them able to enter classes along with those received directly into grade 1.

3. Older men who have been long away from school work and who find mathematical operations and technical reasoning hard. They should immediately be given training in principles and practise along lines in which they need instruction, but with such arrangements that along with this they may gain that knowledge of mathematics and science which will eventually, if they choose to continue their study work long enough, lead as far as the courses arranged for men in grade 1.

Into such an arrangement men may fit who occupy positions of responsibility, or who for special reasons would feel uncomfortable in classes with boys fresh from school, and do excellent work there. The writer has conducted classes of this character in which men over sixty years of age were scholars.

This grade also provides a definite place for men who hold executive positions and want a sort of " business-engineering " training of somewhat indefinite scope.

4. Similar to grade 3 but arranged for boys and young men who must secure a certain amount of technical training at once; or who are not sure until they try it whether their tastes run to a life work along technical lines. Men and boys who seek instruction in trade courses belong in this grade.

A man who followed along any of these lines as far as he could go should have a training equivalent to that of a college or university. His course, however, might be many years in length.

The Part the School Should Take

In any educational scheme the scope of the school work has to be determined and limits set for it. This is as true for vocational education as for any other sort. The writer believes that the tendency of the day in many lines of vocational education is to do too much in the school; while in others the part which schools should take is scarcely recognized.

In vocational work connected with the trades the first difficulty is common. Very many schools give trade instruction in the machinist and pattern-making trades. Starting with these two, it is very easy to expand to include a dozen others, and then the question arises as to why only these particular ones should be taught. Why should not instruction be provided for every trade under the sun? Such elaboration involves requirements in the way of space and equipment which are appalling to contemplate. An army of specialists to teach all these things would have to be found. Now by reviewing the trades and the kind of instruction required in each, it is possible to find certain principles and practise common to large groups. It would be easy to pick a group in which an ability to read drawings is required; fundamentals regarding force, work, power, pressure, etc., apply in all; a knowledge of belting, shafting, and transmission machinery is essential; certain principles regarding the kinds of tools used and how they are best used are needed in every trade. The school can easily give instruction in such lines and its equipment would naturally be planned for it. The direct use of particular machinery, on the other hand, and the detailed application of principles to a particular trade, ought to be gained under strictly commercial conditions in connection with the production of a definite output. This usually involves special methods and machinery distinctive to each plant and factory. Instruction to this end should be given in the factory itself and be specialized to the extreme.

The same thing holds outside of trade instruction. In the electrical industries, if knowledge outside the routine of daily work is desirable at all, much of it applies to *every* line of work. The general principles of direct and alternating current flow come into everything electrical. A knowledge of resistance and im-

pedance once gained, the employee of a telephone company makes the application as readily as the man operating machinery in an a-c. generating station. The generation of e.m.f. by cutting flux and the arrangement of armature windings for dynamos and motors have enormously wide application. The principles are as important to the switchboard man in a central station as to the armature winder in a repair shop. Mechanical thrust on conductors carrying current in magnetic fields of force, and speed and torque relations for motors, have an interest to the instrument maker; while their application is readily made for himself by the man concerned with interurban car work.

The equipment required in order to show a student any of these things is so different from that found in commercial uses, while electrical apparatus once installed affords so little opportunity for intelligent examination of its properties, that no corporation is able to give instruction in such principles to its employees unless the equipment of the school laboratory is duplicated; and if it is, the experienced teacher is lacking. Few people realize how scant are the opportunities to learn in connection with practical work. Regular class work accompanied by individual laboratory experience is the only way. On the other hand, the school can never teach satisfactorily a great variety of subjects important to be known by employees if they are to be of real use to their employers. Such topics are: the arrangement of a distribution system, and why; the use of certain kinds of equipment in connection with certain kinds of installation; kind of insulation used, and why; preferred practise in operating or in dealing with troubles, etc.

Hence, in all sorts of vocational work the school and the corporation each has its own part to play; each a special kind of instruction to give.

Examples of Courses

1. *Drexel Institute* has conducted evening classes for twenty years. The principles upon which they are founded are, that the same opportunities shall be offered as to day students by the same trained faculty used to the work and working together. Every member of the faculty personally teaches evening classes; all the facilities of shops and laboratories are put at the disposal of evening students.

When the work was started, a list of courses like those for day students was made up and offered in evening classes. Instructors met those who came; found what they were seeking and planned

definite classes and inter-relations of classes to meet the requirements. This process has been continued to the present time. One of the remarkable things connected with it is the constant demand for work of still higher and more exacting character. The classes now cover nearly as wide a range as for day students, although they are planned expressly for the men who come to them and are largely elective. The Department of Science and Technology includes mathematics, chemistry, physics, electrical engineering, mechanical engineering, and civil engineering. The classes at present offered by this department include forty different ones, twenty-three being engineering subjects. Definite provision is made to receive students at either the end of grammar school education or the end of a high school course. All students must meet fixed entrance requirements; usually by examination. Any subject may be taken separately if its entrance requirements can be met. Five years ago, on account of a certain demand, elective groupings of higher grade science and engineering subjects were offered, and now a considerable majority of the students are enrolled this way for rather long courses. The normal rate of attendance is three evenings per week for the six months October to March, inclusive. Enough home work accompanies any course to occupy most of the other evenings of the week. The fees are very small. A young man who enters at the point where grammar school closes, must attend for three winters in order to reach a point where he can meet the entrance requirements to subjects arranged for those who have completed a high school course before beginning their evening work. Two more years of training lead to a certificate granted for a "major" in some division of work in the department, and a "minor" in another. Most of the students are quite mature. During the past session 775 men were enrolled; 489 of them for comprehensive courses. A considerable number of students come to the evening classes from points outside the city; some from as far as thirty or forty miles away.

Along with the regular engineering classes certain ones are included of rather elementary character. Applied electricity, as an example of one of them, is given only to mature men, and deals with the topics of dynamos, motors, lights, and wiring. To enter it, a knowledge of simple arithmetic, including mixed numbers, decimals, percentage, and proportion, is required.

In addition to the courses mentioned, Drexel Institute offers shop training to a limited number of men in machine and wood

shop; to a considerable number in drawing courses following old-fashioned lines; to a group in architecture and building construction. The total number of men students in evening classes, 1912-13, is nearly 1100.

2. *The Franklin Institute* has offered evening class work longer than any other school in the vicinity. Courses in chemistry, natural philosophy, mechanics, architecture, and mechanical drawing were established in the spring of 1824. The mechanical drawing classes have been given continuously since.

A dozen years ago a demand arising through drawing work was met by establishing classes in elementary mathematics. A local demand from men employed in the shipyards of the vicinity for training in their line of work came at about the same time. Out of these grew other demands, extending the scope and character of the instruction offered. The work is now conducted in four departments: drawing, mathematics, mechanics, naval architecture. The mechanical drawing is comprehensive; the mathematics includes the high school branches; mechanics includes strength of materials, machine, structural design, and steam engine; naval architecture includes three classes succeeding one another. This last subject illustrates very well the way in which classes have been formed to meet local needs. Philadelphia has two large shipbuilding companies and many smaller ones in or near it. A very close relation exists between these companies and the course in naval architecture.

During the session just completed 305 students were in attendance. Entrance to classes is by certification from Philadelphia schools; by transfer of credits from schools in other cities; by examination. The school year is made up of two terms of fourteen weeks each, the classes being in session from 7:15 to 9:15. Most classes meet two evenings per week. The fees are nominal.

Most people know the Franklin Institute and understand how, through its many activities, the city is under obligation to it. Through lectures, researches, its library, and its *Journal* a very wide educational work is carried on.

3. *The Y. M. C. A.* in Philadelphia is a bureau of information at which very many young men inquire when seeking advice regarding self-improvement. In the past few years it has been decided to establish classes in technical lines. Among other special kinds of work for which a demand has been made is instruction in estimating. During the past session, in the School of Mechanic Arts, classes have been conducted in mechanical

drawing, including shop mathematics; in physics; in applied electricity; and in chemistry (an elaborate course covering the range of college work). At the request of the Department of Public Works of the city government, classes in engineering for power plant operators have been organized with moderate success. A very successful class in practical chemistry for laundrymen affords an example of a real cooperative class arranged to meet a local need. The School of Building Construction includes subjects in "practical work only, taught by practical men." They are architectural drawing, mathematics, building construction, estimating from building plans or specifications; heating and ventilating, including estimates; and electrical construction, including estimates on electrical equipment.

In some of the classes the aid of experienced teachers from the Williamson Free Trades School has been secured.

The laboratory equipment for the work is being gradually increased. Much larger facilities are expected in connection with new building construction about to begin.

The sessions run from the end of September to the end of May, the fees corresponding to those of other local schools.

4. *Temple University*, in its College of Arts and Sciences, offers evening, afternoon, and Saturday classes. One of the original purposes in the founding of this university was the arrangement of a college course for students who could not attend regular day sessions. The work is of the same grade and scope as that undertaken in the day classes and students who have fulfilled the entrance requirements are given credit toward the bachelor's degree for such work. Special students, properly qualified, may be admitted to any of the classes. In forming courses, the subjects are not arranged in the usual plan for four college years, but according to subject matter; the student taking a larger or smaller number of classes according to his circumstances. In technical work a civil engineering department is established, the classes including those usual in a standard college course. The classes are put into five groups: I. Preparatory to engineering groups (mathematics, drawing, chemistry). II. Surveying (including descriptive geometry, railroads, calculus). III. Structural engineering (strength of materials, roofs and bridges, bridge and truss design). IV. Hydraulics (including steam engine and applied electricity). V. Other subjects required to gain the degree of B.S. At the present time no students have advanced beyond the work which naturally falls into the sophomore year of a college course.

5. *Spring Garden Institute* conducts a three-year evening course in electricity. This was originated by the late C. Walton Swoope, whose text book, "Lessons in Practical Electricity," is widely known. The course has the distinct merit of originality and individuality. Students are accepted for the first year's work without any requirement except their wish to follow the course. The first year's instruction is obviously the most difficult for the teacher, and is given partly by lecture and partly by an ingenious system of class laboratory work. Mathematics and science required to understand the electrical work are given as part of the instruction. The first year's class is limited to 150 students; 100 is the preferred number. Students attend two evenings a week. In later years of the course individual laboratory work takes most of the time. The laboratories have a good equipment and the work is well planned. The course includes little or nothing which would be found in an electrical trade course. There seems to be no demand for that kind of work in Philadelphia; the school work is limited to explaining "how" and "why" and verifying the facts by experimental measurements.

The Spring Garden Institute also conducts a course in metal shop work, particularly for machinists, which is attended by a moderate number of students.

6. *The Philadelphia Textile School* of the School of Industrial Art conducts evening classes in a large number of subjects relating to the textile industries. Philadelphia contains between seven and eight hundred spinning, weaving, and knitting establishments, and more than one hundred dyeing and finishing works. The presence of these, along with all the allied industries, including the makers of machinery for these manufacturing enterprises, explains the need of these classes. The evening classes cover in a general way what is given in the day classes. Weave formation, warp formation and weaving; fabric analysis; study of power loom; cotton, woolen, worsted yarn manufacture; chemistry and dyeing; jacquard design, etc., are included, and groupings of subjects are made to meet the particular requirements of each individual case. This is true vocational work given to men who want far higher and better knowledge than simply how to operate the machinery of the industry, a knowledge which cannot possibly be obtained as part of their daily occupation. The laboratories contain a large amount of machinery and appliances which are used in connection with the evening work so far as time available and the nature of their products will permit. The same faculty

which conducts the day classes handles the evening work in the same subjects. Attendance is three evenings per week for the term of six months, the fee for any of the regular courses being $15.

In the art department of the same school, classes are offered in industrial drawing, constructive design, and pottery.

7. *The Philadelphia Trades School* is the first in the United States to be conducted as part of the public school system. It was opened in October, 1906. At the present writing an annex is operated in connection with it (both in the central part of the city), and another school (No. 2), under separate management, is conducted in a different district.

In the evening classes of school No. 1 over a thousand men are receiving vocational training in bricklaying, carpentry, pattern making, electrical construction, architectural and mechanical drafting, house and sign painting, plumbing, printing, sheet metal working. The largest classes are those in electrical construction (216), in plumbing (262), in sheet metal work (142). The two last named form true vocational schools of the cooperative type, for students are not accepted unless they are working at the trades in which they seek instruction.

The whole sheet metal working industry not only endorses the course in this subject and encourages the attendance of workers, but has made attendance at the school part of the apprentice agreement. The students come from fifty-six shops in the city. The course is four years in length and requires attendance three evenings per week for a six months' session in each year. Training in the trade work takes most of the time, but work in mensuration, geometry, simple physics, and mechanical drawing is included.

The fact that the cooperation of the Master Plumbers' Association in the plumbing course is as thorough and satisfactory as that of the Sheet Metal Workers shows their estimate of it. The work follows similar lines to those of the class described in the preceding paragraph. There is no regular apprenticeship among Philadelphia plumbers, but there is a state law demanding examination to secure master's licenses, and graduates who are twenty-one years old (the minimum age) easily meet the requirements.

In most trade courses the instruction is rather closely limited to developing intelligent skill in manipulation. Mathematics or drawing is made to fit closely to the trade requirements. The

class in electrical construction follows [illegible]
There is a mathematics requirement [illegible] winters to graduation. Mathematics [illegible] through trigonometry, and the electrical [illegible] siderable theory along with the trade work.

It is very probable that in the immediate [illegible] may be established with trade organizations [illegible] precisely like that now holding for plumbing [illegible] working. Continuation school work is also likely [illegible] lished in the near future.

8. *The Pennsylvania Railroad.* Within [illegible] definite course of instruction in electrical [illegible] ciated subjects has been offered the [illegible] vania Railroad under the direction of Mr. [illegible] intendent of telegraphs. This is a [illegible] especially to meet the requirements of [illegible] has been well received by those [illegible] prepared is plain when it is stated that at [illegible] eight thousand men have enrolled as [illegible] good for an enrolment of more than ten [illegible] happened without any attempt to urge the [illegible] they have rather clamored for the opportunity [illegible] establishment of the course has, however, [illegible] "electrification" of the system in and around [illegible] The course was launched and the students [illegible] was decided on. The instruction is not [illegible] topics connected with traction problems.

This educational course is not a thing [illegible] simply the last step which has been taken [illegible] ment of efforts made to help those who have [illegible] to secure technical education. Mr. Johnson [illegible] past has been doing educational work with [illegible] employees with whom he has been associated.

When this correspondence course was [illegible] to be started, it developed that men in all [illegible] company wanted to secure its advantages. [illegible] himself says, "Where can the line be drawn? [illegible] employee from the president down, touches [illegible] tions of some kind in his daily routine. It may [illegible] with the telephone or the telegraph, or call [illegible] nection with lighting or motive power. [illegible] departments wants to know something about [illegible]

So far, four well-illustrated pamphlets have been issued, as follows: "General Information," "Mathematics—Elementary Arithmetic," "Elementary Electricity—Primary Batteries," "Elementary Electricity—Direct Current."

The complete course is to cover a wide range of subjects, including drawing, mathematics, telegraphy, telephony, signaling, lighting, electric traction, power plant apparatus, and line construction. In electricity alternating-current as well as direct-current principles and applications are given. The instruction can be secured only by employees of the railroad. The papers and pamphlets are furnished them free of charge with the understanding that they may be kept for future reference. So much work has already arisen in connection with answers to the questions which form the lessons, and from the "question box" which has been established, that branch offices have been opened in Buffalo, Pittsburgh, Altoona, and two in New York.

It is certain that even though only a small proportion of the men who enroll go on to finish the course, all will at least have gained some knowledge. It is with this feeling that the course has been launched; a desire to do as much as possible for employees who are hungry for knowledge, many of whom by environment, location, or character of daily employment have never had the opportunity to learn.

The School of Telegraphy of the Pennsylvania Railroad is another important educational work. This school is located at Bedford, Pa., a location selected so that the expense of a course can be kept to a moderate figure. It was started by Mr. Johnson in 1907 and is of course under the control of his department. Healthy young men between seventeen and twenty-five years of age having a fair common school education are eligible to its classes. Students may enter at any time and are graduated in six or eight months. A small tuition fee is charged, but after graduation this is returned. At graduation all are given positions with the railroad and on proving their worth, are in line for promotion. The school has an equipment for teaching not only telegraph sending and receiving, but also the use of the telephone in connection with railroad work. A complete telephone train dispatching system is in operation, consisting of a dispatcher's outfit and way-stations with selectors. A miniature railway is installed with block signals, etc., on which trains are run, the stations being equipped with main line instruments,

switchboards, and signals, each in charge of a student operator. Block and train orders, messages, and reports are transmitted as they would be in regular service.

The instruction further includes the duties of a station agent; account keeping on the company's regular forms; and the book of rules for the government of the transportation department. At present there are about twenty-five young men in the school.

In connection with the Pennsylvania Railroad Y. M. C. A. work in Philadelphia, there was established two years ago a course of lecture instruction on railway electricity for motive power purposes. During the first year this was of general character, the lecturers using lantern slides, models, etc., to explain in general terms the systems and the apparatus in use for such work. The second year the course has been more definite, more direct instruction methods being used. The class has been in charge of Mr. Eugene P. Chase, electrical instructor of the Pennsylvania Railroad at the New York terminal. With the aid of full-size interurban car equipment, the work has been made very practical. The writer has been particularly interested in this class, as the result of his having the honor and pleasure of giving the instruction at the beginning of the course on the general fundamental principles which apply. It has been remarkable to observe how a class of sixty men, many of them in mature life, most of them holding responsible positions, such as road foreman of engines and the like, have held together through bad and cold weather with a constant, lively, maintained interest. The course closes in April. Another class is formed immediately.

In connection with machine shop apprenticeships at the West Philadelphia shops of the railroad, there are regular classes operated on the "continuation" plan, attendance being compulsory and on the company's time. The instruction is handled from Altoona, and was outlined in the 1912 report of the Educational Committee of the Institute on "Industrial Education."

9. *The Bell Telephone Company's Plant Schools in Philadelphia.* Eight years ago an installer's school, primarily for the systematic instruction of the employees of the plant department of the Bell Telephone Company, was established. An enormous increase in plant extensions to meet the demand for telephone service had to be made and the required number of trained maintenance employees and private branch exchange installers could

not be secured. During 1906 the company enlarged and perfected the school work, carrying on a Central Office School and separately a Private Branch Exchange School and a Substation School including line and cable work. These schools have been abandoned. They were required and considered a necessary part of conducting the telephone company's business while thirty per cent, or less, of the men of the plant department were unskilled workers. Today probably 90 per cent of the employees are trained men, and in connection with their every-day work they, or some of them, assume the responsibility for the proper instruction and training of apprentices or helpers.

While the schools were operated, they were managed by men whose whole time was given to teaching, and were so conducted that regular instruction in electrical theory, in so far as it would apply to the practise of the company in telephone work, was given in a systematic school way. The equipment included circuit charts and standard apparatus. The methods of practical instruction were carefully worked out to fit the requirements of the case, and as many as forty students were cared for at one time, an average of 300 students passing through the schools per year. Not only new employees, but older ones, were brought into the schools, the number attending at any time depending on the amount of work then in progress or in prospect. In the case of *new* employees about seventy-eight per cent passed the instruction work with an average considered sufficient for continued employment. The Substation School was of lower grade than that dealing with central office equipment and apparatus. Admission to the Central Office School was granted ordinarily only to those who had had the other training and a considerable amount of practical experience. The period of instruction in each school was about six weeks, during which period each scholar was paid his regular rate of wages. Some graduates of the school deserted the company, but the loss due to this cause was not considered a serious factor in determining the commercial value of the schools.

10. *Firms and Corporations* conducting school work for their employees in Philadelphia or its vicinity are very few. The large department stores have such classes, but those which are vocational are not technical. The only firm doing anything directly is Fels and Company, as noted in the next paragraph. The New York Shipbuilding Company (Camden, N. J.) has an apprenticeship system including four years of 2500 hours each. A

definite time allowance is made for time spent in the classes of a selected list of schools, based on the actual attendance of each man, governed by his averages and the benefit he has derived from his studies. No arrangement is made for instruction in the shipyard because of the proximity of schools in Philadelphia and Camden. William Cramp and Son's Ship and Engine Building Company in its electrical department has an arrangement somewhat different from the usual apprenticeship system, which has been in operation for six years. Each apprentice spends three months' time in a particular department of work and passes from it to another only after he has been examined and shows that he knows what he has been doing. No instruction of a class room kind is given. What he learns he picks up in connection with his every-day duties.

A number of boys and young men are employed in the soap-making works of Fels and Company whose positions, in the nature of the case, lead nowhere. Realizing this, and believing that such young men should have definite opportunity for advancement of some kind offered them, the firm gives each one the opportunity to spend one week in four in the machine shop, where as definite a course as possible is laid out for them. At the end of three years these men are assisted to positions in other firms where they advance in the machinist and kindred trades. In addition, free evening drawing classes are open to the same men during a considerable part of the year, the firm supplying the necessary equipment.

11. *Education for City Employees.* Those at the head of the present city government realize that in city employ, as in any private undertaking, the matter of the educational advancement of the individual employee is of prime importance. The Mayor, therefore, a few months ago secured the appointment, through the Superintendent of Public Schools, of an advisory committee from the faculties of the various high schools, who should on request direct men and women engaged in the city's service how to improve themselves, so as to be in line for promotion. This committee met semi-monthly from November to April inclusive, during which time 180 persons from the Departments of Public Works and Public Safety, the ones most interested, called for counsel. They have been given advice as to existing educational opportunities in schools, have had courses of reading suggested, etc. Some thirty-five of the number wanted to secure engineering training of collegiate character.

At the present time in Philadelphia, except for the Trades Schools already mentioned, there is no vocational training available in the public school system for those who are employed. The only agency prepared to deal in a broad and disinterested way with the subject of vocational education and vocational guidance for both those now employed and the young people still at school, is the Public Education Association (composed of a volunteer membership of a thousand citizens). Through its secretary a solution to the many problems is being sought.

12. *Electrical Department of the Underwriter's Association.* A novel movement with an educational motive was started a few months ago when the chief of the department, Mr. Devereux, invited inspectors of the city, inspectors and managers of the Philadelphia Electric Company, and electrical contractors and their superintendents to the semi-monthly meetings of the inspectors of the Philadelphia Fire Underwriters' Association. Starting with thirty, the number attending has increased to one hundred and fifty. The character of the meeting has become one of free discussion and question asking—very much more educational than most such gatherings. The topics discussed are the National Electrical Code, city regulations, and any puzzling subject which may be brought up through a question box which is opened at each meeting.

13. *The School of Industrial Arts*, Trenton, N. J., is the only school within a range of many miles from Philadelphia providing vocational education for those who are employed. It was established 1898 in pursuance of "An Act Providing for the Establishment and Support of Schools for Industrial Education" approved by the Senate and General Assembly of the State of New Jersey, March 24, 1881. The act provides for "the establishment and support of schools for the training and education of pupils in industrial pursuits (including agricultural) so as to enable them to perfect themselves in the several branches of industry which require technical instruction."

The school is supported by the state of New Jersey and the city of Trenton. Courses in machine, building, electrical and pottery trades are offered. The school has had a fine building erected for and presented to it in 1910, an equipment which is adequate to the work undertaken, and a director endeavoring to make the school fit the industrial conditions. Trenton has large pottery industries, rubber works, wire mills, and a railway repair shop. There are over 600 students in the evening classes.

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THE PENNSYLVANIA RAILROAD COMPANY APPRENTICE SCHOOLS

BY JOHN PRICE JACKSON AND J. W. L. HALE

In dealing with the subject of the Pennsylvania Railroad Apprentice Schools, certain explanations are necessary, inasmuch as this system of schools has been developed on a plan somewhat different from those maintained by most other large industrial or transportation corporations.

The cardinal purpose of the corporation named—in harmony with that of others—is to prepare young men for efficient service in the mechanic arts related to its particular business. In this case many of the young men will later become locomotive firemen and engineers, skilled mechanics in engine and car shops, operators in power plants, draftsmen, etc. It was, therefore, very carefully determined at the outset that the apprentice school work should be so given as to develop in the young men a proper ambition to become skilled in work of this character and at the same time to avoid developing in them the discontent and unhappiness which comes to those whose aspirations are beyond their capability or circumstances—as would be the case if they were led by their instructors to believe that they should attain positions in which manual skill and labor is not required. Incidentally, however, it was carefully specified that such records should be kept as would enable the company to lay hold of the small percentage of the total number of apprentices who, by reason of exceptional brain power and ability, should be advanced beyond the ranks of skilled workmen to the ranks of those who direct the labor of others.

Though the purposes and aims stated in the last paragraph are carefully observed, nevertheless the directors of these schools

frankly admit that they are more largely schools of the mind than is usually admitted in the case of similar institutions. However, the work of the schools is carefully related to the work in the shops, and there is very *close affiliation between superintendents and foremen in the shops and the instructors in the schools.* Foremen are the shop instructors of the young men. The reason for this unusual arrangement is the belief of those in charge that a foreman who has the intelligence and capability to do his work well, and who has a sufficiently broadminded interest in the progress of his organization, will likewise have the ability and desire to instruct the apprentices efficiently. It is indeed believed, and experience has shown the truthfulness of the belief, that good foremen are unusually efficient in following up and teaching these young men. By having the whole responsibility on his own shoulders, so far as the shop instruction goes, the shop foreman must, of necessity, take a personal interest in the advancement of the apprentice. Failure on the part of the latter is directly debited to the former by the general officials. The fact that a single man in a department has this responsibility and that it is, therefore, not divided between foreman and shop instructor, with the consequent unsatisfactory results of divided authority, is an argument well worth consideration.

The apprentices are moved from department to department of the shops very much as in other establishments, and have carefully arranged shop apprenticeship courses. A complete system of records prevents young men from being held up unduly on any particular branch of the work, and keeps the company officials and school instructors fully informed concerning the comportment of the young men while in the shops. In the following pages the schools proper are described. It must not, for that reason, be thought that there is any neglect of the training of the apprentices while in the shops. This feature has been worked out in great detail.

The Pennsylvania Railroad Schools now consist of the parent institution established in Altoona, Pa., where the number of apprentices attending is in the neighborhood of 260, and the more recently established branches located in Philadelphia, Pa., Wilmington, Del., and Harrisburg, Pa., in which the enrolment ranges approximately from twenty to thirty-five and forty. The exact number of students enrolled is not here given, since it varies somewhat from month to month. In establishing the schools, the railroad company officials were anxious to make use

of well-established pedagogical methods and at the same time maintain a very practical course of applied education. The company, therefore, called upon the School of Engineering of the Pennsylvania State College to formulate the pedagogical methods to be pursued and to take general supervision of the schools. As a result, the system has been worked out and is carried on as a co-operative movement between the college named and the railroad officials. An instructor in charge of the entire work is located in Altoona; he is assisted by four other instructors and sufficient clerical service. One instructor only, at the present time, is required to carry on the schools in Philadelphia, Wilmington, and Harrisburg, the remainder of the force being located in Altoona.

In the following brief outline of the work done by the schools and the methods adopted, ordinary names of subjects as used in schools and colleges are given. This is done because, though these subjects are all prepared for a special purpose and are correlated closely with the work the young men are doing in the shops, they may, nevertheless, with entire propriety, be given their proper names. In some cases special terms, such as "shop mathematics," etc., are used in describing the work of schools of this class. As a matter of fact, the nomenclature in use in our ordinary schools is entirely sufficient for the purpose of denominating these subjects, if it be kept in mind that they are different only in regard to the illustrations, arrangement, etc., of the old, well-established principles.

Monthly, semi-annual, and annual reports of the work of the schools and of the individual apprentices are made out by the head instructor and include attendance, grades for each subject studied, average grades, and comments upon characteristics and capacity. These reports are voluminous and are of such a character as to form a fairly complete record of the aptitude and ability of each man. The records thus obtained, when taken into consideration with the parallel system of reports from the shop foremen, form a most valuable body of data from which selections for the various services of the corporation may be made, and also give the instructors an accurate basis upon which to sift out undesirable material and make proper promotions in the schools. It may be interesting to observe here that a small percentage of the young men show extraordinary ability, and that the company officials have been materially aided by the schools in drawing into their official ranks the very cream of the

entire body of apprentices. Without these detailed and well-established records, many of these men would never have reached the positions of maximum value to the company, with a resultant great loss, not only to the men themselves, but to the corporation. One of the members of the company has made the statement that this possibility, made available through the schools, of picking out accurately the unusual material from the mass, is in itself of sufficient value to warrant the entire expense involved in maintaining the schools.

The work as outlined covers three years of forty-two weeks each. The apprenticeship course itself is of four years' duration. During the last year the apprentice does not attend the school unless detailed thereto, but is assigned special work by the company to give him particularized training for the duty which he is later to perform as a skilled workman. Each apprentice receives four hours of instruction per week in periods of two hours each. These two-hour periods are separated by as many days as the schedule will permit, in order that the lessons assigned may more readily be given as much evening consideration and study as is possible and desirable. The recitation work calls for about an hour of daily study, which must be done during the evening by the apprentice.

In dividing the body of the apprentices into sections, an endeavor has been made to give an individual instructor from fifteen to twenty men in a class. Much flexibility with regard to the classes is maintained; thus, if it is found that a section can be made up which will travel much more rapidly than the average, such a step is taken, or *vice versa*, if a group of the less bright men can with advantage be segregated and given the work in more detail, that arrangement is made. It will be appreciated that this kind of instruction requires more labor on the part of instructors than if an entire class covers exactly the same work, but by using these methods it is possible more nearly to give each individual the training which is best for him, and thus more effectively to prepare him for the service of the company. The necessity of careful class selections is marked in the case of these schools, as the apprentices are drawn from all classes and enter with schooling which ranges from the common school grades to those of a college. Using the ordinary names, adopted among teachers, the curriculum in the school might be said to include a rudimental study of English, mathematics, physics, mechanics, mechanism, strength of materials, chemistry, mechanical drawing, machine

design, steam practise, and shop management. This sounds like a formidable list of studies extracted from some catalogue of a technical college, but as a matter of fact it represents, in reality, a very elementary but thorough system of study dealing with simple phenomena of nature, methods of computation, and the English language, closely allied and correlated with the daily labor of the apprentice pursuing the studies. Indeed, the school authorities want it clearly understood that this school is of a most practical type for improving the quality of skilled mechanics, and not for making half-prepared engineers. Moreover, they wish it to be known that the life of the school has been sufficient to determine the fact that it is accomplishing this function well.

The work in English covers spelling, the meaning of words, parts of speech, formation and construction of sentences, and composition writing, including accurate methods of writing business letters, making out order blanks, time reports, etc. The young man when he is through with this course not only has gained some practical ability to use understandable English, but also to comprehend better such reports and instructions as may be given to him either by word of mouth or in writing.

The work in mathematics begins with very simple shop problems in arithmetic, including the elementary processes of addition, subtraction, multiplication and division, fractions, decimals, etc. Gradually this work is advanced to bring in applications involving some of the most useful elementary principles of algebra, geometry, and trigonometry.

The course in physics includes both class work and laboratory work in elementary principles of heat, electricity, and mechanics, and a short study of light and sound. Practical illustrations very closely allied to the shop work are used exclusively, and the course is given specifically for the purpose of enabling the apprentice to have a keener conception of the processes that take place under his hands while at work. Numerous problems of this character relating to the field of mechanics will immediately arise in the minds of those reading this who are connected with the industries.

The mechanism parallels the work in mechanics and is an applied study dealing with motion, velocity and acceleration, power work, etc., as shown by study of shop machines.

The study of strength of materials deals with the manufacture and properties of materials used in machine construction. Along with this are carried out tests upon various materials in order to give the apprentice a vivid conception of the strength and other characteristics of materials with which he deals in his work.

The chemistry taught includes some of the more fundamental facts which every man connected with industry should know about the chemical reactions and constitutions of materials. Special stress is laid upon the characteristics of water and fuels and the combustion of the latter. Inasmuch as a large number of the apprentices become locomotive men, the importance of combustion as a study directly pointing to the proper use of the boiler firebox is evident.

The course in steam practise deals with such problems as should be understood by locomotive engineers or firemen. In this, as in those subjects heretofore named, the work is very practical, but it is to be clearly understood that much care is at all times exercised to emphasize the underlying physical principles upon which practise is based and to bring the apprentice as far as possible into touch with the phenomena involved, through the medium of his senses.

In mechanical drawing, the student becomes familiar with the standard methods of drawing, dimensioning, and lettering. Models built in the shops are used for sketches from which mechanical drawings are made. These courses are sufficiently extended not only to give some skill to the apprentice in presenting his ideas accurately on paper, but also to enable him to read shop drawings accurately and readily.

The machine design course is a continuation of the work in mechanical drawing and presents enough of the elementary principles of design, including the study of strength and stresses, to enable the apprentice to have a rough conception of the principles underlying the methods of determining the conformation of machine parts. The work is not intended to produce designers, but to develop common sense with regard to the strength of machine or structure parts.

The work in shop management includes lectures upon shop arrangement, departmental and stock room reports, cost and time keeping, and economical methods of handling work. The course is intended to enable the apprentice to fall into his duties and his organization with intelligence and efficiency. Indeed, it is believed that this course of lectures is a necessary one for the young man whom it is expected to develop into maximum service to his corporation.

The texts for these courses of study have been largely prepared by the instructors in the apprentice schools and by the Pennsylvania State College. Before beginning the preparation

of the texts, a careful study was made of similar work prepared for other corporation schools and such published texts as were available. However, the texts themselves were written with direct reference to the kind of training it was desired to give in these particular schools. In obtaining the instructors for the schools, it was thought best to use college graduates who had had experience in the industries. Though it is difficult to find good men of such training for the salaries that are usually available for work of this nature, these schools have been quite successful, and the instructing corps has proved itself to be efficient, both from the standpoint of the shop manager and the standpoint of the pedagogue.

Experience with these schools has clearly shown that the use of the proper principles of pedagogy in work of this kind is as important as in any other kind of school work. Indeed, this statement might be made stronger and revised by the statement that proper pedagogy is more important in this kind of school work than in most other branches of education. As a result, the employment of instructors who are not thoroughly capable from a pedagogical standpoint, however expert they may be in their own particular vocations, is a serious error and is bound to result in comparatively unsatisfactory results.

DISCUSSION ON "INDUSTRIAL EDUCATION" (REPORT BY EDUCATIONAL COMMITTEE), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

Charles L. Clarke: The papers upon education which have been read this evening relate to industrial education directed toward the improvement in efficiency of the workmen in the various industries and the minor technical men connected therewith, all generally definable as laboring men, nevertheless of widely varying degrees of intelligence and skill. Hence, it is, specifically, vocational education.

The purpose is to make such men as a whole intelligently skilful in their calling, and therefore, more useful to their employers. Incidentally, it will result in a few men, with greater natural talents and force of character than their fellows, advancing from the ranks to assume executive positions of greater or less importance. Furthermore, it will undoubtedly vastly improve the relations between labor and capital, to their great mutual advantage.

It is not the speaker's purpose to traverse the matters relating to vocational education that have been presented in these papers except in one particular. The details can, obviously, best be handled by professional educators, who make a specialty of these lines of training.

Now, to the point that the speaker has particularly in mind—it is the teaching of good English composition, which has been referred to briefly in the papers by Mr. Rowland and by Prof. Jackson and Mr. Hale. Along with the study of matters vocational and cognate subjects, the study of English should diligently be pursued throughout the entire course, not merely in a formal way, as determined by the educators, but through notes and examination papers handed in at frequent intervals, which should be corrected by the English teacher and instructively commented upon before the class. Proper improvement and perfection in composition should be insisted upon, on a par with proper advancement in other studies.

Digressing for a moment from strictly vocational education, the study of English should be insisted upon in the student courses for graduates of technical colleges, which are now pursued in the works of some of the large manufacturing corporations. Deficiency in ability to write good English (which includes, of course, correct spelling) is nowhere more apparent than among young men just out of college, and this defect does not wear away any too rapidly with the progress of the years.

It is a serious handicap to them, and especially to skilled but uneducated artisans, who are liable keenly to feel this defect which the speaker has often observed, like a weight bearing them down and making it appear to them useless to try to rise above the lower level in which circumstances have placed them.

Drill the artisan in good English, make him conscious that he can talk and write with respectable correctness. It will conduce

to clearness and conciseness of expression, which are most important adjuncts; will help discipline his mind and make him a clearer thinker, besides increasing his self-respect, all of which will make him more valuable to his employer and also to himself.

A professor of rhetoric in Harvard University has stated in his text-book on the subject that although there may be good English there is no such thing as perfect English. Therefore, an effort to reach the unobtainable may not be made; perfect English is practically out of the question; the English of the scholar is unnecessary; nevertheless, ability to speak and write passably good English should play a serious, substantial part in vocational education.

Henry G. Stott: It seems to me the keynote of the whole situation in regard to industrial education occurs just in a single sentence in the paper by Prof. Jackson and Mr. Hale, with which I heartily agree. It is as follows: "It was, therefore, very carefully determined at the outset that the apprentice school work should be so given as to develop in the young men a proper ambition to become skilled in work of this character and at the same time to avoid developing in them the discontent and unhappiness which comes to those whose aspirations are beyond their capability or circumstances—as would be the case if they were led by their instructors to believe that they should attain positions in which manual skill and labor is not required."

It seems to me that is the keynote of the whole situation and it points to a grave danger in this so-called trade school and industrial education by corporations. The company with which I am connected has done a good deal of this work, but we do it mostly with a view of finding out what the men know, so as to be able intelligently to select men for promotion. We fear there is a very great danger, as noted here, of storing up in men false ambitions and false ideals such as that it is not quite as honorable or as reputable for a man to work with his hands and have a suit of overalls on, as it is to have a clean job as a clerk at $50 or $60 a month, and there is a tendency, especially with the young foreigners, to set up these false ideals as to the value of education.

I do not wish to underrate the value of education, because no one can get too much of it, but a great many of our high schools seem to teach wrong ideals in many cases, and I believe the whole secret of success is in finding out which of the men are ready for promotion, and which of the men really deserve to be promoted, and not in the attempt to give them a smattering of instruction in a few subjects. We know, when it comes to engineering work, that we must have men who are thoroughly trained in the fundamentals of physics, and we select our engineering group from college men, as in the company I am connected with, but before promoting our men to the minor positions of responsibility we use the training schools to find out which of the men are thinking seriously. Perhaps once a year we find a man who should be encouraged to try to work his way through college, and we help

him all we can. Three or four men in the last three or four years have made very creditable records, but that is a very small percentage, probably less than ¼ of one per cent of the employees, so that I think the point of view announced here in the paper by Prof. Jackson and Mr. Hale is really the keynote of the whole situation—that we must be careful not to store up false ambitions in a man who is incapable of being promoted, because he has not the ability or the necessary education, and it is distressing to see him become discontented and unwilling to work at honorable trades at which he could earn three or four times as much as a clerk makes. The result of this dissatisfaction is that he goes out into clerical employment, and he finds that he is in the midst of a host of competitors for what he calls a clean, respectable job.

M. T. Crawford: In my connection with the public utility company in one of the Western cities, I have found that there are many young men at work during the day in the city, who would like to study further. I would like to bring out in a little further detail the work which is accomplished by the universities in some of these far Western cities.

The University of Washington, in Seattle, for instance, gives a course in electrical engineering covering four years leading to the degree of B.S.E.E. and with the fifth year giving a degree of M.S.E.E., and after three years in a responsible position the degree of E.E. is given. In addition to this regular college work, night classes are held for advanced study and research work by technical graduates who are engaged in practical work during the day in the city. Separate night classes are also to be given this coming year of a more elementary nature for men who have not completed the University courses, but who have met the requirements of the University, who have to work during the day. The latter are standard courses and University credit is given for the work. A considerable amount of special work has also been done by the regular students from time to time for the larger companies, such as oscillograph tests and special research work, which gives them a direct practical contact with operating conditions.

J. W. L. Hale: The apprentices serve four years and are moved from one department to another as stated in the paper. This is done so that they may have a varied experience. We feel that we lose nothing by giving them a broader idea of the work in the several departments of the shop as well as that in which they are more directly interested. Many of these apprentices will ultimately be called upon to fill positions of minor responsibility in shop management, and therefore this knowledge of other departments is necessary.

I might say along the line of the questions which have been raised that apprentices, when they go into the school, have open to them all of its privileges and they are bound to make improvements along general lines. However, the matter of education of apprentices, as it appeals to us largely, is in regard

to developing their powers to comprehend instructions which are given them and to make reports properly, etc., etc. You appreciate the necessity of this in the operation of a railroad. It is necessary that they have such a knowledge as will enable them to understand instructions and make reports intelligibly.

Regarding the aspirations of apprentices for something higher than that for which they are suited, I have spoken of our schools as selective media. The boys who come to us are of all grades of ability, and it is for us to line them up and put them into that part of the organization in which they properly belong.

So far as our experience extends the boy has not become dissatisfied with his condition through the fact of further instruction. We think a great deal depends on the instructors as to the ideals which they put before the boys. If they teach them the honor of labor, and instill in their minds that, by attention to their duties, promotion is open to them, and that some of the railroad mechanics earn more than professional men, it seems to me that this difficulty can be overcome to a large extent.

The Pennsylvania Railroad is only one which has taken up the matter of an apprentice school instruction system. There are at least eight, and possibly more, representative roads that are engaged in the same work. These extend from the Atlantic to the Pacific, and the work is progressing very rapidly. This is one of the principle features of work which is being taken up in the new organization, the National Association of Corporation Schools. The matter of corporation industrial education is not new but is well afield.

J. Lloyd Wayne, 3d: I believe in all matters of this kind the difference between success and failure may lie in the local traditions of the community in which you are situated. For instance, in the East, where both a man and his family will undergo considerable personal hardship to give him an education, you can go a great deal further in this matter of education than you can in a community where practically none of the families will undergo any hardship to have their young people go beyond the education which is required by law. If you try to introduce industrial education or similar activities amongst people of that kind, you are apt to run up against this condition which I have seen,—many of the men will feel that to join these classes gives them a pull to get ahead. Some of them do not, of course, but I have known of a school where it was discovered a large majority of the pupils attended with that motive in view, having no motive for attendance except the standing which they felt attendance at the school gave them with the boss. They really did not get much out of it and the school was abandoned.

This state of mind on the part of the pupils was found to be not exceptional, but quite general. One whose experiences have been gained in the East exclusively is likely to overlook the fact that in a relatively young country there is not much ambition to secure an education, and more people are satisfied to work along a

certain number of prescribed hours, and have their endeavors end with that, rather than to take up any additional work in the form of study.

A. M. Buck: Although we have been talking this evening almost entirely about instruction, I think we have forgotten the instructor. In any scheme of industrial education he is one of the most important factors, and a careful choice should be made to secure the proper man for the work. In the college or university the instructor is often chosen because he was a good student, and perhaps has done excellent work after graduation. This, of course, gives no indication that he has the proper personality, or that he is especially fitted to instruct others. In some cases he may succeed, especially if his work be along the lines of research, where he does not come into intimate contact with students. When, however, we consider the choice of teachers in industrial or trade schools, I think the personality of the instructor is of vital importance, and believe that it is absolutely essential to choose men for this work who are in close touch with the situation. Furthermore, they should be able to inspire the men in their charge. I have had but little experience with vocational training; but I do know a number of college professors who have given inspiration to their students and brought out a great deal more work from them than is ordinarily obtainable.

Another point which comes up in this connection is the training of the instructor. In many cases he is simply turned loose on his work without having had any special training, and often without definite instructions of any kind. The necessary training is not given in many of our technical schools, but I believe it should be. At least the instructor should be told exactly how to go about his work to produce the best results. I think many instructors who might be very successful fail because of their inability to appreciate the situation. Had they been properly directed at the beginning, and understood thoroughly the proper attitude toward the students, as well as how to impart their knowledge, much good might have resulted both to themselves and to their students.

F. C. Caldwell: Much has been said this evening about the value of vocational training as given by industrial concerns, as a help in the selection of men to do the work for which they are best fitted. The two aspects which this work seems to take on are these: first, the work of the industrial concerns in training their own men, and second, the work of the universities and other institutions in training those who either are not yet connected with any manufacturing concern, or in training those who are so connected during their spare time. There is one point, that I was glad to hear Mr. Stott speak of and which needs to be emphasized; that is the importance of being on the look-out for the unusual case, for the ¼ of one per cent, that is for the man who ought not to remain a mechanic, but who ought to be encouraged to go ahead and secure a college training, so as to become an en-

gineer and a leader. We need all of this type of men that we can possibly secure. The supply now is not equal to the demand. It may not be generally known that the supply of college-trained engineers is decreasing, while the demand is increasing; that throughout the country the engineering colleges have not been increasing in the number of their students during the past four years and in many cases they have actually decreased. This is largely due to the growth of the agricultural colleges and general development of the agricultural movement. We therefore need in our engineering colleges, all of the men that we can possibly get, that are of the right kind out of which to make engineers. This is one of the things which vocational training in industrial concerns should accomplish, the picking out of the exceptional man, who is just the man to send through college, to receive a course in engineering, and to be turned out as a competent engineer.

The other point is the work being done in the line of vocational guidance outside of the industrial concerns. There are, as you may know, societies in many of the larger centres whose object is to study the subject of the vocations in which the boys and girls may engage, and to try to guide them into those vocations which will give them the best use of their abilities and yield the greatest return to society from the results of their endeavors. We know that there is a tendency for the boy, when he leaves school, to pick up some stray job like selling tickets for a moving picture show or something of that sort, which will yield him some money immediately, but which leads to absolutely nothing in the future, and the object of the vocational guidance societies is to try to educate the school children into the idea of looking forward to their life's work and planning for it, even before they have left school. It seems to me that this is a very important feature of this work which our committee might do well to consider.

H. M. Friendly: There is a phase of education which I think has been sadly neglected in colleges and in various institutions of learning, and that is encouraging the students in the reading of technical magazines and periodicals. You cannot impart experience to a man, but you can impart knowledge to him in various ways—by reading periodicals and other literature, and reading the experiences of men who have superior ability to observe phenomena, etc. A man will often get in touch with practical matters, and gain a degree of experience in reading about them, possibly better than he might by actual contact with the work. With all due respect to the colleges, I have had occasion to observe that the men they turn out, or at least most of them, are deficient in that one thing, and I also find that many of the men that come out of the colleges and other educational institutions, because of their failure to read technical literature, fall by the wayside.

Mr. Carron: There are two or three points upon which not enough emphasis has been put in the discussion of the papers this evening, and one of these points is, in order to make real progress in educational matters the fundamental principles of educa-

tion must be applied to these vocational courses just as they are to the more advanced courses, and a great deal of the fault in the past with vocational courses, which have sprung up here and there, is because they have not been carefully organized, have not been put in charge of men who have made a study of educational problems, and the result has been these various deficiencies which have been pointed out. In one class the instructors try to instill too great an ambition in the minds of the students, and succeed in getting them discontented with their particular line of work and more harm than good is done. In another class the instructors do not appreciate the advantage of picking out the occasional individual and giving him the personal instruction which is needed; but the fact that a group of papers of this sort is brought up for discussion at a meeting of this nature and the fact that more attention is being given to the subject along these lines is encouraging to us who are interested in educational problems.

George C. Shaad: I wish to take some exception to the points brought out in regard to the matter of the care now being taken in selecting instructors in all classes of educational work. I believe the personal side of the instructor is receiving, in the better grades of institutions, as much, if not more, attention than the purely theoretical knowledge which the particular candidate may possess. It is only by securing coöperation and one institution profiting by the failure of another that much can be done through these organizations for industrial education, and if these institutions will profit by the failures of the past as much real progress in this line as in any other line of education can be made.

O. J. Ferguson: There is an unfortunate thing which develops in the course of the instruction of college classes, and that is that some 30 per cent or perhaps 50 per cent of the men in the classes ought never to have gone to college. I believe that one of the most encouraging features for those who are taking up the matter of vocational training is to be looked for in the possibility of the selection of our raw material. I believe that if we were able to make the selection of the raw material when it comes to us, rather than taking a great deal that should not be allowed there, the results that are attained from college education would be greatly improved as well.

Comfort A. Adams: My interest in the subject before us is not so much that of the professional educator as that of the citizen and engineer, and the point I wish to make relates to certain broad aspects and ideals of social and educational efficiency.

In the youth of our country we have the raw material which undergoes some degree of refinement and adaptation to useful ends, in our various educational institutions. The varieties are only limited by the number of individuals, some are fitted by nature for one life task and some for another. To make the most of this raw material is the problem of education, and the degree in which we succeed in wisely *sorting* it and then in *developing* it in each of the numerous fields of service to its maximum

usefulness, is a measure of the real efficiency of our educational system.

The problem of developing such material as now comes to our various schools and colleges, and the increase in the variety of fields in which education is offered, are common subjects of discussion, but it is to the subject of *sorting* that I wish to call your particular attention.

For the purpose in hand let us divide the youth of the country into two groups: one group including those to whom the higher or professional education is now open—less than 5 per cent of the total—and the other group constituting the remaining 95 per cent. Some may disagree with my figures and say that every really strong young man has this opportunity if he is willing to work; but such are the rare exceptions and I am talking of averages. If the rare exceptions were alone to be considered, the problem of education would be a simple one. Actual statistics will show that my 5 per cent is a very liberal allowance.

Within this small group there are many who are not able to profit by their opportunities and who are, as a result of professional training, actually unfitted for occupations more adapted to their native ability, such occupations being considered beneath a college man. On the other hand, there is undoubtedly much material in the larger group well able to take full advantage of the highest educational opportunities, but prevented from so doing by no fault of its own. All this is a great burden upon and loss to society, a burden in attempting to instruct the unfit, and a loss by the waste of much good material sent out into the world without appropriate training. A young man's college tuition fee pays ordinarily not more than one third of the cost of his instruction; the other two thirds is contributed directly or indirectly by the community at large, except in the case of state universities where *all* of it is so contributed. Thus all of those young men who are not profiting fully by this training, who are not being really educated (and this number is not small) are burdens on the community, even though they are paying tuition.

The industrial training here under consideration, is a good thing because it offers to those in one group an opportunity to increase their efficiency within that group, but it does not fundamentally change the situation or touch the root of the real difficulty. It does not appreciably increase the opportunity for the passing from one group to another better adapted to the native capacity or ability of the individual in question, it does not appreciably improve the "sorting" process.

I grant you that this difficulty is a fundamental one and that it is entangled with the very roots of our social order, but it is well occasionally to realize the defects of that social order and to turn our eyes towards an ideal if one is available. The nearest approach to a solution of the problem lies in what might be called the competitive system of education, in which the degree and variety of education open to any individual is *wholly* dependent

upon his ability to profit by the opportunity, as determined by competition. (I here use the word "education" in its narrow rather than in its broad sense). A somewhat distant approach to such a system is now in operation at West Point and Annapolis. Under our present social order, educational opportunities beyond the legal requirement of a primary schooling, are largely dependent upon the length of the parents' bank account. In other words, the present basis of "sorting" our "raw material" is most crude and irrational.

Mr. Stott speaks of the danger in the proposed system of industrial training, that some young men may be educated beyond their ability to make good or to profit by it. This is exactly what I have tried to point out in connection with our present system of higher education, except that it is vastly greater in the latter case owing to the fact that many men are in college largely because of the money back of them, whereas, the men in the various industrial or apprenticeship courses are usually on their merits. It has also been stated that men attend these courses in order to "stand in" with their employers or bosses. A boss not able to judge of a man on his merits is hardly fit for his job. But in the college this becomes a real danger. A boy from a well-to-do family is sent to college and is made to feel that he must follow some "profession," when in fact he is not fitted by nature for any of them. He may be a good mixer, he makes friends and connections in families of wealth and is boosted and pulled along into positions which he fills with little satisfaction to himself or anyone else, while thousands of men with the ability and character which he lacks, are wasting that ability and making poor manual laborers for lack of educational opportunities. This all means social waste and inefficiency. We too rarely stop to realize that the more nearly each unit in a social group can be developed to its maximum usefulness, the better off will every other unit be.

Let us then lend our hearty support to any step which extends our system of vocational training, which broadens the range of educational opportunity, but, let us at the same time remember that with ever so varied a range of offerings, we are yet a long way from any reasonable social efficiency if we say to this or that class in our society, you may be educated only in this field, these other opportunities are closed to you.

Briefly, we must pay greater attention to the "sorting" of our raw material.

Harry Barker: There are two matters which have been mentioned, the one by Professor Caldwell and the other by several members. Professor Caldwell spoke of the work of vocational guidance which has been started in a number of places, and the others have mentioned the need of weeding out unfit men in college courses, and in vocational courses to a certain extent. These two things may go hand-in-hand in the elementary public schools. A start has been made to carry out such work along

psychological lines, but so far the work has largely been along economic improvements. There are ways in which you can detect abilities, tendencies, bents, etc., but only a few people in the country have any real knowledge which can be brought to bear practically on this matter. Yet a start has been made and it is well for engineers to keep in touch with this particular phase of vocational guidance. The one man in the country who can speak with greatest authority on this phase of vocational guidance is Professor Muensterberg, and he is going into the matter seemingly very deeply. He seems desirous of sharing the results of his studies and has published many details of his procedure.

The ways in which we can detect budding ability and bent or trend towards certain qualities need to be considered along with bureau work which makes vocational guidance stand for certain economic improvements. We do not want to lose sight of mental scrutiny in the great stress which is being put upon industrial opportunities.

Arthur J. Rowland: The general topic for the present report of the Educational Committee is "Industrial Education." This is also carried at the heading of each page of my part of the report. It was not my intention to limit what I had to say to that education which trains men in industry or in the industries; but rather to consider education planned to train those working in the industries for wider usefulness, and for higher places. Relatively little of what I have described has for its aim the training of routine workers; the object is rather to develop intelligent understanding of why a given routine method is used, and the principles behind it, along with an appreciation of the relation of science and technical subjects to everyday affairs. Such training fits a man for greater usefulness with the corporation for which he works in the position he holds; and also makes him available for advancement to places of higher responsibility. The interest most corporations take in the education of their employees seems to center on this last fact. A man who is worth anything, who has been tried out in a humble place where his personal qualities have become known, is preferred for advancement to a higher place, if educational limitations are not too great, above the one who comes in unknown and untried.

The scope of the paper has been limited to that education offered to men who are employed and to the subjects which have to do with industrial and technical training. In my paper I have not attempted to deal with this subject exhaustively. I have not included every school in Philadelphia and vicinity. I may not have done justice to the evening school work of the Public School System of Philadelphia. The statements made near the top of page 1435 are based on the fact that except for trade school courses the subjects offered are, almost all, those belonging to *regular* high school work. The city of Camden, N. J., just across the Delaware River, has taken hold of the prob-

lem of industrial education in a very careful way through its Superintendent of Public Education, and is now giving evening instruction in wood, metal working, and in elementary mathematics. Certain firms have been, in a limited way, undertaking instruction (of the school kind) for their employees.

At this present time I believe it is safe to say that nothing has been done in Philadelphia in the way of "continuation" school work except as noted in the last section of the Committee report in certain of the Pennsylvania Railroad shops. There is a pretty strong feeling among Philadelphia educators interested in vocational work that continuation schools may be all right in Germany; but that this kind of work to be successful must be limited to countries where class distinctions are closely drawn and the highest aim in the education of a worker is therefore to make him thoroughly skilled in his own line and sufficiently intelligent to find "joy in his work." In America every man is pushing for higher places in the shop and in the social scale; for better and fuller recognition of his best capabilities. Such a condition is fundamental in a democracy like ours and all education should take account of it.

In my paper I call attention to the fact that in Philadelphia the various schools have each developed the kinds of education they offer, and the subjects of instruction they are prepared to give, in a thoroughly individual way. This has a certain kind of merit. It also has some serious faults. Since the paper was written an effort has been made to associate all the institutions offering evening instruction in technical subjects, especially those relating to engineering, for purposes of better mutual understanding and in order to afford a means of dealing with the educational problems of our city in a direct way as a unit. The advantages of cooperation have already been felt and during the summer it is probable that much will be done to correlate properly all this work, to associate it with needs and wishes of manufacturers and corporations, to have it properly understood by the general public. It has developed that there is as much value to be gained by educational institutions who come into close association in a definite organization as there is by manufacturers and business men in their trade organizations. At the present time in Pennsylvania there is a good deal of stir about educational matters, especially in relation to those who have not had or cannot have the advantages of the standard forms of education. The organization of Philadelphia schools, etc., just referred to, is likely to become identified with a state-wide movement for educational uplift.

A tendency of our day is to establish many kinds of schools and many subjects of instruction, especially in industrial and technical lines. I believe there is danger of creating too many. The newer kinds of vocational training proceed from the concrete to the abstract; from practise to theory. This leads to all sorts of trade instruction as fundamental. The number of trades is

almost limitless and the fundamental principles connecting with them are relatively few. A little vocational guidance work would show workers and those interested in their education the need of instruction in principles, and much more than in practise. Many illustrations might be given, but I will not take time for them. Planning mainly for the teaching of principles, a few classes only for which there was large demand might be organized. A constantly increasing number of specialized classes offering new problems in teaching and new requirements in text-books would be avoided.

Corporation schools are beginning to attract considerable attention. Specialized instruction will always be required in every business and industry in order to qualify its workers to meet its individual problems well and intelligently. Such instruction the school cannot give, since each of its classes has members from among the employees of many corporations. On the other hand, the corporations cannot plan to teach principles and general subjects, which are fundamental and necessary prerequisites to intelligent specialized instruction, unless they duplicate the equipment and faculties of existing schools. Since such schools commonly require heavy endowments or state appropriations in order to operate, the expense to a corporation (if the work is well done) is prohibitory.

Many societies claim to have educational work in connection with their monthly or bimonthly meetings. This always takes the lecture form and is "smattering" in character. Its value is much over-estimated. A man doesn't know a technical subject unless he can talk on it himself and work out problems connected with it. This can be secured only by *systematic* training accompanied by recitations under a teacher.

Correspondence school work is also of small value. Unless supplemented by direct instruction, and, in many subjects, by opportunities to conduct personal experimental work, not much can be learned. The experience of most evening schools with correspondence school students who seek them proves this.

Referring now to the paper, at page 1421, we find my feeling about evening school work, based on twenty years of experience in it.

In training workers for wider and higher usefulness in their chosen vocations, the education must be restricted in scope; given by an experienced teacher who can respond to the difficulties of his scholars; and must be laid out so that a worker in a humble place can be trained for a position higher up, attaining which, the training for something still further on can be secured, and on and on indefinitely. Such opportunities are being developed more and more in evening school work in Philadelphia. The same thing could be done in part time schools of a "continuation" type, and it is hoped that somehow this will be tried out in the near future.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

(1) SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE SUSPENSION INSULATORS

BY F. W. PEEK, JR.

The insulators specified herein are to be of the link suspension type for use in a........ volt circuit. The dielectric must be homogeneous, symmetrical, and not appreciably warped.

Surface of Dielectric:

The entire exposed surface of the dielectric must be smooth, uniform, and impervious to moisture. The dielectric must be moisture-proof throughout, and in case a glaze is necessary on the surface it must be smooth, hard and firm, and uniformly applied. The dielectric surface of the insulators must be durable and unaffected by the weather, ozone, nitric acid or nitric oxides, or sudden changes in temperatures over the atmospheric range.

The requirement for imperviousness shall be as follows:

The sample for test must not have a glazed surface, and the volume must be in the neighborhood of 2 cu. in. (30 cu. cm.). It must be dried at 120 deg. cent. until weight is constant, and then immersed in water for 48 hours. The temperature of the water to be between 20 and 40 deg. cent. It is then removed from the bath, the surface water rubbed off with a cloth, and weighed. It must not have absorbed water to the extent of more than 0.25 per cent of its original weight.

Cement:

When cement is necessary in assembling the dielectric and metal parts, it must be strong and durable—not the weakest point—and should preferably be rendered impervious to moisture,

unaffected by changes in weather, ozone, nitric oxides, or sudden changes in temperatures over the atmospheric range.

If the cement contains organic compounds, the flow point must be over 90 deg. cent.

Fragility:

Designs must be of rugged construction and so formed that there will be a minimum exposure of any fragile part to missiles from below.

Length of Complete String:

Total length of complete string of units including cable clamp should not be more than— ft. (—cm.), nor less than— ft. (—cm.)

General Design:

Practical considerations being equal, preference will be given to the design applying best scientific principles in regard to the dielectric circuit.

TESTS

Factory Test:

Every single disk or unit shall be tested for two minutes continuously with the voltage held at 10 per cent below the arc-over point.

Three completely assembled samples of each type of insulator to be considered shall be subjected to the following tests, and the purchaser reserves the option to subject one out of every two hundred to the same tests.

Arc-Over Tests:

The complete insulator or assembled string shall have a sufficient number of disks in series so that while dry the arc-over potential (effective sine wave) shall not be less than three (3) times the operating voltage (between lines), and not less than $2\frac{1}{2}$ times the operating voltage when exposed to a spray at an angle of 45 deg., giving 0.2 in. (0.5 cm.) precipitation per minute.

While under the above rain test the insulator must be able to withstand a continuously applied potential of $2\frac{1}{4}$ times the operating voltage for five minutes. The specific resistance of the spray water must be between—and—ohms per cm. cube. These potentials shall be supplied by a 60-cycle testing set, giving approximately a sine wave.

Throughout these electrical tests the string of insulators is to be supported on a grounded metal arm, and the voltage is to be applied between this arm and a 6-ft. (2-m.) length of cable

—the same as is to be used on the transmission line. This cable is to be gripped firmly in a clamp, and to project three ft. (1 m.) on each side. The potential shall be applied at not over half arc-over voltage, and increased at the rate of about 1000 volts per second.

Arc-Over String:

Arc-over should take place completely across the string, and not from unit to unit in cascade. Preference will be given to the insulator which most closely fulfils this condition.

Corona:

At 1.3 times line voltage there must be absolutely no sign of corona or static discharge on either the insulators of the assembled string, or any of its fittings. Other conditions being equal, preference will be given to the insulator for which the corona starting point is nearest the arc-over point.

Voltage Balance of String:

The ratio of the measured arc-over voltage of the string to n times the arc-over voltage of a single unit shall be determined, n being the required number of units in a string. Competitive tests must be made at 60 cycles and on the same transformer and generator. Insulators are to be supported from grounded metal arm as above, and arc-over voltages measured on string lengths of from one to n units. Other conditions being equal, preference will be given to insulators showing best balance along the string.

If, in the opinion of the engineer, the "multigap effect" at high frequency, on account of large metal parts or for other reasons, is probable, a special high-frequency string arc-over test may be called for.

Uniformity Test:

Twenty-two single disks or units taken at random from stock, and which have passed factory test, shall each in turn be placed in oil, potential not exceeding half arc-over voltage shall be applied, and gradually increased at the rate of about 1000 volts per second until puncture shall occur. Any twenty of these puncture voltage values shall then be selected. The difference between the maximum and minimum puncture voltage must not be more than 20 per cent of the average voltage. The average puncture voltage must be not less than 30 per cent above the dry arc-over voltage.

Special Test

Impulse Test:[1]

Twenty-two units shall be selected at random. Each of these disks shall be connected in turn to the impulse circuit shown in Fig. 1. The gap *A* shall be set (60 cycles) at three times the arc-over voltage of a single unit. The voltage shall be increased until gap *A* arcs over, when the circuit shall be immediately opened by breaker. This shall comprise a " stroke."....strokes shall be applied to each unit, or until puncture occurs. Preference shall be given to the insulator showing the greatest uniformity and the highest average puncture voltage. Referring to Fig. 1, the shunt condenser capacity shall be— microfarads, and the inductance—— millihenrys.

NOTE: The above test will show, in a general way, the probable effect of surges, lightning, etc., on the life of the insulator, as well as uniformity of the porcelain. The number of strokes, and

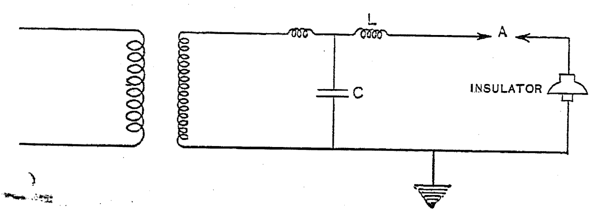


FIG. 1

the voltage to puncture, will depend upon wave front of impulse, on frequency, etc. This cannot now be definitely specified, as the phenomena have not yet been sufficiently investigated. A test as above, however, is very important in competitive tests.

Method of Measurement:

Unless otherwise specified, the tests are to be carried on and voltages measured by the sphere gap, as proposed for the Standardization Rules of the American Institute of Electrical Engineers. The voltage shall be controlled in such a way as not to distort the wave form. It is preferred that it be controlled by a regulator consisting of a shunt resistance directly across the low-voltage side of the transformer, and a series resistance in the supply circuit. The shunt resistance must always by-pass at least five (5) times the exciting current of the transformer. The

1. See *High-Frequency Tests of Line Insulators*, by Imlay and Thomas, TRANS. A. I. E. E., Vol. XXXI, 1912, p. 2121.

principal control is effected by the series resistance. This method is often spoken of as a potentiometer method.

The sphere gap voltmeter must be corrected for temperature and barometric pressure. A water tube or non-inductive metallic resistance of about one ohm per volt of test voltage should be placed directly in series with the gap. The arc-over voltage and corona-starting voltage must refer to the average barometric pressure where the insulators are to be used and at a temperature of 25 deg. cent.

Mechanical Stress Tests:

After it has been decided from the electrical test how many disks shall constitute a suspension unit, this number shall be attached in a string, together with the adopted suspension hook and cable clamp, and a load[2] of —— lb. (——kg.) shall then be applied without rupture or signs of distress in any part of the string.

Mechanical Inspection:

A mechanical inspection shall be made of all insulators and those shall be rejected which contain open holes or cracks in the glaze or porcelain, or are not perfectly cemented. The inspector shall use a light-weight mallet to rap each part and note the soundness of the ring. Occasional samples of the ware shall be broken to see that they do not contain air cells or foreign matter.

Protection of Metal Parts:

Metal parts must be made of non-corrodible metal or be heavily galvanized.

General

The insulator makers shall be required to furnish all facilities, equipment, and labor for making tests and inspection, as specified above, and shall at all times allow free access to such facilities and equipment by the authorized representatives of the purchaser until the entire order is inspected.

2. Depending upon the size of the conductor to be used and the wind and ice load allowed.

(2) SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS

BY J. A. SANDFORD, JR.

Specification for Suspension Type Insulators

General:

(a) These specifications are intended to cover the design, quality and manufacture, including inspection and testing, of ....porcelain insulators, cat. No..............

(b) The operating voltage will be..........................

(c) There will be required approximately......................suspension insulators, each of which shall consist of..........................units.

(d) There will be required approximately..........................strain insulators, each of which shall consist of..........................units.

Metal Parts:

All cap castings intended for cementing to the top of the porcelain parts shall be of the best grade of malleable iron. All studs or center pin forgings intended for cementing into the hole in the under side of the porcelain unit, shall be of the best grade of steel forging.

Galvanizing:

All cap castings and center pin forgings shall be galvanized by the hot dip process, and must be capable of standing the A. T. & T. immersion test for one minute. All fittings failing to meet this test shall be rejected.

See separate specifications covering galvanizing in detail.

Porcelain:

All insulators shall be made of a dense, homogeneous porcelain best adapted to high-tension insulator requirements, free from

injurious cracks and flaws or other injurious defects that would render them unfit for the purpose intended. The burning of all porcelain sections shall be done so as to insure thorough vitrification.

Glazing:

Unless otherwise specially agreed upon, the glazing will be brown and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement.

Absorption:

Porcelain shall be practically non-absorbent. A test section broken from any insulator shall not show an absorption of more than one tenth of one per cent of its weight.

Electrical Tests before Assembly:

After inspection to eliminate faulty material, the unassembled porcelain disks shall be given a regular routine electrical test at a point just below flash-over potential for five minutes. If puncture occurs in the fifth minute, the tests must be continued until no puncture occurs in one full minute of test. All parts failing to meet this test shall be rejected.

Assembly:

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, throughly mixed, and the proper stiffness for the nature of the work. The assembly shall be so done that no hollow or voids will be left between these cemented surfaces and all superfluous cement must be cleaned off of the insulator before crating.

Mechanical Test:

After approximately ten days' setting of the cement, all units shall be given the regular routine mechanical test of —— lb. (—kg.), with tension applied in line with the axis of the insulator.

Final Electrical Test:

All units shall be tested electrically to 95 per cent of flash-over for one minute.

Design Tests:

The dry arc-over value of the assembled insulator, consisting of——units, shall be not less than—— volts, potential applied for one minute.

The wet arc-over value of each insulator, consisting of —— units, and tested under standard precipitation of 1 in. (2.5 cm.)

fall in five minutes at an angle of 45 deg. with the horizontal, shall be not less than——volts.

At the option of the purchaser or his engineer, the contractor shall conduct tests to demonstrate the dry and wet flash-over values given above, but inasmuch as these tests are for proving correctness of design only, not more than five insulators of the same design shall be required to be subjected to the tests.

The average ultimate mechanical strength of the insulator shall be not less than 8000 lb. (3630 kg.).

At the option of the purchaser or his engineer, one tenth of one per cent of the number of units so covered by these specifications, may be tested to destruction, but only such units as are rejected for other causes shall be used in making this test.

Inspection:

The contractor will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at contractor's pottery.

The inspection or waiving of inspection will not relieve the contractor from obligation to furnish material in accordance with specification.

Crating:

All insulators shall be assembled and packed one per crate ready for suspending from the towers. The crates will be of the contractor's standard design.

Should the contractor's design of crate not be satisfactory to the purchaser or his engineer or inspector, contractor will change same to suit the purchaser's requirements, with the reservation that at the contractor's discretion he may or may not still assume the responsibility for the safe transportation of the material affected by the change. Further, should the revised crate specified by the purchaser, his engineer or inspector, cost more than the contractor's standard crate, the difference shall be charged to the purchaser, which difference in accepting these specifications the purchaser agrees to pay.

Drawings:

Drawings showing detail of units and spacing of units in complete insulator are herewith submitted.

Specifications for Pin Type Insulators

General Information:

(a) These specifications are intended to cover the design, quality and manufacture, including inspection and testing, of .... porcelain insulators, cat. No.........................

(b) The operating voltage will be........................

(c) There will be required approximately........................ insulators made up of........................ parts, catalog No.........................

Porcelain:

All insulators shall be made of a dense, homogeneous porcelain best adapted to high-tension insulator requirements, free from injurious cracks or flaws or other injurious defects that would render them unfit for the purpose intended. The burning of all porcelain sections shall be done so as to insure thorough vitrification.

Glazing:

Unless otherwise specially agreed upon, the glazing will be brown and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement.

Absorption:

Porcelain shall be practically non-absorbent. A test section broken from any insulator shall not show an absorption of more than one tenth of one per cent of its weight.

Electrical Tests before Assembly:

After inspection to eliminate faulty material, the unassembled porcelain parts shall be given a regular routine electrical test as follows:

All parts of the insulator before being assembled will be tested for............ minutes at the voltages mentioned below. Should any part be punctured in the............ minute of test, the test will then be continued until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two quantities of water.

The voltages to be applied to the several insulator parts will be as follows:

Head..	volts
Second shell..................................	"
Third shell....................................	"
Center...	"

All parts failing to meet the above tests will be rejected.

Assembly:

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, thoroughly mixed, and the proper stiffness for the nature of the work. The assembly shall be so done that no hollow or voids will be left between these cemented surfaces, and all superfluous cement must be cleaned off of the insulators before packing.

Final Electrical Test:

All complete assembled insulators shall be tested electrically at..................volts for three minutes. This test is to be applied in the same manner as the tests for parts described under "Routine Tests."

Design Tests:

The dry arc-over value of the assembled insulator, consisting of............parts, shall be not less than............volts, potential applied for one minute.

The wet arc-over value of each insulator, consisting of............ parts, and tested under standard precipitation of 1 in. (2.5 cm.) fall in five minutes at an angle of 45 deg. with the horizontal, shall be not less than............volts.

At the option of the purchaser or his engineer, the contractor shall conduct tests to demonstrate the dry and wet flash-over values given above, but inasmuch as these tests are for proving correctness of design only, not more than five insulators of the same design shall be required to be subjected to the tests.

Mechanical Test:

The insulators covered by the specifications must be capable of withstanding without signs of distress a pull of 2000 lb. (910 kg.) applied at the tie-wire groove in a direction at 90 deg. with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

Inspection:

The contractor will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor,

etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at contractor's pottery.

The inspection or waiving of inspection will not relieve the contractor from obligation to furnish material in accordance with the specifications.

Packing:

All insulators shall be assembled and packed in.................... each containing...................insulators. The...................will be of the contractor's standard design.

Should the contractor's design of................ not be satisfactory to the purchaser or his engineer or inspector, the contractor will change same to suit the purchaser's requirements, with the reservation that at the contractor's discretion he may or may not still assume the responsibility for the same transportation of the material affected by the change. Further, should the revised...................specified by the purchaser, his engineer or inspector, cost more than the contractor's standard.................... the difference shall be charged to the purchaser, which difference in accepting these specifications the purchaser agrees to pay.

Drawings:

Drawings showing detail of the complete insulators covered by these specifications are herewith submitted.

Supplementary Directions and Explanations

Minimum Distance from Insulator to Grounded Objects:

As this factor does not enter into the commercial testing of insulators we recommend that it be neglected and the standard practise of the manufacturer accepted.

Number of Insulators to be Tested at one Time:

As there are several hundred sizes of porcelain parts to be tested we recommend that the number of parts under test at one time be such as to suit the manufacturer's convenience, except that the number shall not be so great as to take more than the full load current of the testing transformer, or make it impossible to hold the test voltage at the required point.

Factor of Safety—Dry:

We recommend that the dry flash-over voltage of any insulator be not less than three (3) times the normal voltage at which it is to operate.

Factor of Safety—Rain:

We recommend that the wet flash-over voltage of any insulator under standard precipitation of 1 in. (2.5 cm.) of water in five minutes directed at the insulator at an angle of 45 deg. with the horizontal, be not less than 175 per cent of the normal voltage at which it is to operate.

Quality of Water for Rain Test Purposes:

As this is one of the greatest, if not the greatest variable entering into the rain test, we recommend the use of condensed steam water. This can be easily obtained in any factory or laboratory. Pressure at 45 or 50 lb. (20-23 kg.) by means of an air pump completes an outfit that is satisfactory and the results obtained will be such that they will check very closely with those of other investigators.

Inasmuch as the results are comparative only, we feel that this is the best solution of the difficulty, even though the quality of the water may be slightly better than that met under operating conditions.

Angularity of Spray:

Standard practise has placed this at 45 deg. with the horizontal, the axis of the insulator being in the vertical postion. We see no reason for changing this practise.

Dew Test or Condensation of Steam on Insulator Surface:

We would recommend that this test be eliminated as giving no data that may not be obtained otherwise.

Testing Capacity of Equipment:

This is a matter of little importance so long as the number of insulators tested at one time does not load the transformer to more than its rated capacity, thus making it impossible to hold the voltage up to the required point, and may, therefore, be left to the manufacturer.

Method of Control of Voltage:

The method of using the field rheostat of the alternator as a means of control is offered as being the most desirable from all points of view. The low-tension winding of the testing transformer may be easily arranged so that for a given test voltage the generator may be worked at such a point on the saturation curve as not to cause any trouble from wave distortion, due to weak field excitation.

Control by means of an induction regulator taking current from a constant-potential circuit may also be recommended as

offering few objectionable features and as being very convenient in some instances.

Control by water rheostat in the primary circuit should be used only in cases especially arranged so that distortion of wave form will not occur or where much distortion will be unobjectionable.

The potentiometer method of control is well adapted to laboratory work where the number of tests to be made is comparatively small and the work is intermittent. For regular factory testing of insulators, however, this method is very expensive, due to the large amount of power being continuously expended in the resistances.

Grounding of One End or Middle of Testing Circuit:

As applying to all regular or routine tests this point may be left to the convenience or standard practise of the manufacturer. Special test or method of connection should be left for decision between the parties concerned.

Frequency of Test Voltage:

Any commercial frequency from 25 to 133 cycles, inclusive, may be used for regular factory routine tests. Special tests at frequencies not included above are to be covered by special specifications as occasion requires. This is intended to cover so-called "high-frequency or impulse tests."

Method of Measuring Voltage on Test Circuit:

The method of measuring the voltage on the test circuit shall be that method recommended by the American Institute of Electrical Engineers, covering such cases.

We suggest, however, that instead of taking spark gap readings for every test, the manufacturer calibrate his equipment, thus securing a curve between low voltage and spark gap readings which will be found to be sufficiently accurate for routine work and a very great time saver in making the tests.

What Constitutes Breakdown of an Insulator:

To the insulator manufacturer and probably the larger part of the engineering profession, "breakdown" of an insulator means failure by puncture, thereby totally destroying the usefulness of the insulator in question. We recommend that this term be understood in this sense.

Regarding corona, brush discharge, static streamers and arcovers we regard the conditions as different degrees of distress, and the manner of observing and recording them is open to discussion. The appearance of these various degrees of distress

is very irregular and uncertain and varies greatly on the same insulator with varying conditions of test.

The ultimate arc-over value of various styles of insulators may be obtained individually, but we recommend that the only way in which satisfactory comparisons of these other various degrees of distress on different styles of insulators can be made is to test all styles to be compared, at one time, in parallel, and in a dark room, when these differences can be seen and a fair record made.

Tests for the Puncture Strength of the Insulator:

Tests on a certain per cent of each 1000 insulators should be made to determine the ability of the insulator to resist puncture. This test is best made by submerging the insulator in oil. The nature of the test is such that it cannot well be specified to apply to more than a small percentage of the number of insulators covered by the specifications.

In testing suspension insulators under oil for puncture value, the porcelains should be completely assembled with the standard fittings, (or equivalent), with which they are to be used in service.

In the case of pin type insulators there should be attached, to the head of the insulator, wire representing the tie and line wires, and a metal pin should be assembled in proper manner in the pin hole.

The test voltage should then be applied to the fittings in each case. The average puncture value obtained under these conditions should not be less than 135 per cent of the dry flash-over voltage of the complete insulator in question.

In order to be able to compare results of tests made by different investigators, it is necessary to standardize the manner of applying the voltage as regards the time element involved. We recommend the following:

Apply to the insulator a voltage 20,000 volts below the dry flash-over value for 30 seconds, then raise the voltage by 10,000-volt steps until puncture occurs, holding the voltage constant at each step for 30 seconds.

For testing sample disks of porcelain not made up into insulator shape, we recommend that spheres ½ in. (12.7 mm.) in diameter be used as terminals.

Simultaneous Mechanical and Electrical Test:

We recommend that this test be eliminated from the list of commercial tests, as we feel that it is purely a laboratory proposition and that at best the results of such tests are very unreliable.

(3) INSULATOR TESTING SPECIFICATION FOR INSULATORS HAVING AN OPERATING VOLTAGE EXCEEDING 25,000 VOLTS

BY PERCY H. THOMAS

Introductory:

This specification gives the conditions of tests and inspections which are found best to secure reliable high-tension line insulators for use under the ordinary conditions of power transmission work. It is expected to serve as a skeleton or model specification and may be supplemented by such additional matters as may be appropriate for any particular case.

GENERAL SPECIFICATION COVERING ALL TYPES

1. (a) This specification is intended to cover the inspection and testing as to design, quality and manufacture, of .... porcelain insulators, cat.No.............................., of .... Company.

(b) The operating voltage is..............................

2. *Drawings:*

A dimensioned drawing shall be furnished showing the complete insulator and, if the insulators are built up or composed of a string of elements, showing also each element.

3. *Inspection:*

The maker will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at maker's pottery.

The inspection or waiving of inspection will not relieve the maker from obligation to furnish material in accordance with this specification.

4. *Design:*

All insulators shall be designed to fail by flash-over and not by puncture.

Insulators shall be of robust construction and design so as not to be easily injured in handling.

The ultimate criterion of the merit of an insulator is its performance in service and the best practical measure thereof is its behavior under definite tests. However, as no practicable tests actually reproduce service conditions, for example in the matter of high-frequency voltage, criticism on theoretical grounds is valuable, and, other things being equal, preference should be given to the insulators most closely conforming to theoretically best designs.

Metal Parts

5. *Corrosion:*

All metal parts shall be of non-corrodible material or shall be galvanized in accordance with the specifications for galvanizing prescribed by the joint committee of the National Electric Light Association in its specification for overhead crossings of power lines above telephone and other low-voltage lines.

6. *Factor of Safety:*

Metal parts shall have a factor of safety of at least three over the maximum strain that they may receive in service, except that with pins for pin type insulators the factor may be reduced to two where a higher factor is impracticable.

Porcelain

7. *Quality:*

All porcelain parts shall be made dense and homogeneous as is best adapted to high-tension insulator requirements, free from injurious cracks and flaws or other defects that would render them unfit for use in insulators. The burning of all porcelain sections shall be done so as to insure thorough vitrification. The surface shall be smooth and uniform and moisture-proof.

8. *Glazing:*

The glazing shall be .... and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement. It shall be unaffected by weather, ozone, nitric acid, nitric oxides, alkali dust, or sudden changes in temperature over the atmosphere range.

9. *Absorption:*

The requirement for imperviousness shall be as follows:

The sample for test must not have a glazed surface, and the volume must be in the neighborhood of 2 cu. in. (30 cu. cm.). It must be dried at 120 deg. cent. until weight is constant, and then immersed in water for 48 hours. The temperature of the water to be between 20 and 40 deg. cent. It is then removed from bath, surface water rubbed off with a cloth, and weighed. It must not have absorbed water to the extent of more than one-tenth of one per cent of its original weight.

Cement

10. *Assembling:*

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, thoroughly mixed. The assembly shall be so done that no hollows or voids will be left between the cemented surfaces and all superfluous cement must be cleaned off of the insulator before crating.

Electrical Testing

11. *Wave Form:*

The wave form of the generator shall be true sine curve within the limits specified for generators by the Standardization Rules of the American Institute of Electrical Engineers.

12. *Control of Voltage:*

The voltage shall be controlled in a way not to distort the wave form. It is preferred that it be controlled by a regulator consisting of a shunt resistance connected directly across the low-voltage side of the transformer, and a series resistance in the supply. The shunt resistance must always by-pass at least five (5) times the exciting current of the transformer. The principal control is effected by the series resistance. The method is often spoken of as a potentiometer method.

For routine tests other methods of variation of potential may be used, provided such routine test apparatus has been calibrated by an approved method for the actual parts or groups of

parts to be subjected to the routine test. Such calibration shall be made on the maximum number of pieces to be used in the routine test.

13. *Measurement of Voltage:*

The method of measuring the voltage on the test circuit shall be that method recommended by the American Institute of Electrical Engineers, covering such cases.

For routine work, instead of taking spark gap readings for every test, the maker may calibrate his equipment by the approved method of voltage measurement, thus securing a curve between primary voltage and secondary spark gap readings, which curve may be used to determine the secondary voltage. Such calibration shall be made on the routine test apparatus with the maximum number of parts to be actually used in the routine test.

14. *Kilowatt-Ampere Capacity of Testing Apparatus:*

The kilowatt-ampere capacity of the testing apparatus is important, for the leading current taken by the insulators tends to distort the test voltage. The maximum current taken from the test apparatus should not be so great as to distort the voltage wave sufficiently to cause a condenser to take more than .... times the current[1] it would take on a true sine voltage,[2] and the current taken from the test apparatus shall in no case exceed full rated load.

15. *Surrounding Conditions During Tests:*

With insulators intended for lines not exceeding 75,000 volts no object other than leads and support should approach nearer than 6 ft. (1.8 m.) to the insulator. For insulators intended for lines of higher voltages the conditions for the "design test" of complete insulators should be made as nearly as practicable the same as the conditions of actual service as regards the grounding of one side of the insulator and the arrangement and distance of grounded objects. A conductor of 6 ft. (1.8 m.) or more in length, extending equally on both sides of the clamp, should be used to represent the transmission wire.

Routine tests not being on completed insulators do not require these precautions, but in each case the method of making routine

1. See paper by C. M. Davis, this volume, p. 775.

2. This may be determined by the formula $I = n\ V\ C$, where I is amperes, V is volts, n is cycles per second and C is capacity in microfarads.

tests shall be calibrated when the surroundings are different from those here prescribed.

16. *Frequency:*

Tests should be made at the frequency at which the insulator is to be used. Where special agreement is made, tests must be made at 60 cycles on insulators intended for use on higher and lower frequencies. No error of a serious magnitude will be expected within the range of 25 to 133 cycles.

17. *What Constitutes a Breakdown:*

An insulator is said to "fail" under a voltage test whenever a puncture occurs in any part of the insulator or when a discharge of any sort passes from one terminal to the other, since such a discharge would be followed by an arc on a power line.

Local breakdown, either corona or local sparks, is an important symptom of weakness, and indicates possible bad performance under other conditions. The weight to be given local breakdown, however, is a matter of judgment and is best considered in the light of simultaneous competitive tests.

18. *Rain Tests:*

Water should be sprayed on the insulator at a uniform rate averaging 1 in. (2.5 cm.) depth in 5 minutes, and should be reasonably uniformly distributed over the whole insulator. The rate of precipitation shall be measured by collection of water in a pan at the location of the insulator, the insulator being removed. A satisfactory spray in the form of a fine mist can be obtained by some forms of atomizers where pressure is available.

The spray shall strike the insulator at an angle of approximately 45 deg.

The water used shall have a high specific resistance, not less than .... ohms per cu. in. (..................... ohms per cu. cm.). Pure water may often be obtained from condensed steam or melted ice, or rain.

When insulators are to be used in localities subjected to salt spray or alkali mists special tests should be made.

Oil Tests:

Tests on a certain percentage of each 1000 insulators, not exceeding $\frac{1}{4}$ of one per cent, should be made to determine the ability of the insulator to resist puncture. This test is best made by submerging the insulator in oil.

Suspension insulators should be completely assembled with the standard fittings with which they are to be used in service.

With pin type insulators there should be attached to the head of the insulator, wires representing the tie and line wires, and a metal pin should be placed in proper manner in the pin hole.

The test voltage should then be applied to the fittings in each case. The puncture value obtained under these conditions should not be less than 135 per cent of the dry flash-over voltage.

In making the test, apply to the insulator a voltage 30 to 40 per cent below the dry flash-over value for 30 seconds, then raise the voltage by steps, until puncture occurs, at a rate of about 1000 volts per second.

PIN TYPE INSULATORS

19. *Inspection:*

All parts should be inspected before assembling.

20. *Electrical Tests Before Assembling:*

All parts of the insulator before being assembled will be tested for three minutes at the voltages given in the following table. Should any part be punctured in the last minute of test, the test will then be continued until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two bodies of water.

TEST OF VOLTAGES ON PARTS

Head..	volts
Second Shell..................................	"
Third shell...................................	"
Center..	"

21. *Final Electrical Tests:*

All complete assembled insulators shall be tested electrically at 10 per cent below the flash-over voltage for three minutes. This test is to be applied in the same manner as the tests for parts described for Routine Tests, §§12, 13 and 15.

22. *Design Tests—Mechanical:*

The following design test shall be made on enough complete insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the behavior of the design and the uniformity of the product.

The insulators covered by these specifications must be capable of withstanding without signs of distress a pull of .... lb. (............ kg.) applied at the tie-wire groove in a direction at 90 deg. with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on the pin to be

used in service. In case of failure the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

23. *Design Tests—Electrical:*

The following design tests shall be made in enough complete insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the performance of the type. The insulator shall stand without failure:

A *dry arc-over* test of not less than three times potential between line wires applied for one minute.

A *wet arc-over* test of $2\frac{1}{4}$ times the potential between line wires for one minute.

SUSPENSION TYPE INSULATORS

24. *Inspection:*

All parts shall be inspected before assembling.

25. *Electrical Tests Before Assembling:*

The unassembled porcelain disks shall be given a regular routine electrical test at a voltage 10 per cent below flash-over potential for five minutes. If puncture occurs in the fifth minute, the tests must be continued until no puncture occurs in one full minute of test.

26. *Mechanical Test:*

After approximately ten days setting of the cement, all units shall be given the regular routine mechanical test of .... lb. (........... kg.), with tension applied in line with the axis of the insulator.

27. *Final Electrical Tests:*

All disks shall be tested at a voltage 10 per cent less than flash-over for two minutes. If puncture occurs during the last minute the test must be continued until no puncture occurs in one full minute of test. This test shall be made after the mechanical test above prescribed, §26.

28. *Design Tests—Electrical:*

The following design tests shall be made on enough complete assembled insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the performance of the type. The insulator shall stand without failure.

A *dry arc-over* test of the complete insulator, consisting of .... units, of .... volts, applied for one minute.

A *wet arc-over* test of each insulator, of .... volts.

It is preferable that the arc-over of the complete insulator shall be over the insulator as a whole and shall not be over the individual elements.

There is no advantage in a dry flash-over strength greatly exceeding the wet flash-over strength and there is the disadvantage of the greater danger of puncture. The wet flash-over voltage should not be less than twice the voltage between line wires.

29. *Design Tests—Mechanical:*

At the option of the purchaser or his engineer, one-tenth of one per cent of the whole number of assembled parts forming one element may be mechanically tested to destruction. Where practicable such units as are rejected for other causes shall be used in making this test.

APPENDIX

The following tests are recommended as desirable where appropriate. They are not incorporated in the above tests as experience with them is not yet sufficiently broad.

30. *Uniformity Test:*

Twenty-two single disks or elements taken at random from stock which have passed factory test, shall each in turn be placed in oil, potential not exceeding 30 to 40 per cent of arc-over voltage shall be applied, and gradually increased at about the rate of 1000 volts per second until puncture shall occur. Any twenty of these values of puncture voltage shall then be selected by the maker. The difference between the maximum and minimum puncture voltage must not be more than 20 per cent of the average voltage. This test should be repeated with one or more additional groups of 22 disks, not exceeding in the aggregate $\frac{1}{4}$ of one per cent of the total, enough to determine the uniformity of the product.

31. *Impulse Test:*

Twenty-two units shall be selected at random. Each of these disks, or preferably several disks in series, shall be connected in turn to the impulse circuit shown in Fig. 1, p. 1460. The gap A shall be set at three or preferably four times the arc-over voltage of a single unit. The voltage shall be increased until gap A arcs over, when the circuit shall be immediately opened by breaker. This

shall comprise a "stroke." .... strokes shall be applied to each unit or string of units or until puncture occurs. Preference shall be given to the insulator showing the greatest uniformity and the highest average puncture voltage. Referring to Fig. 1, page 1460, the shunt condenser capacity shall be............ microfarads, and the inductance .... millihenrys.

NOTE: The above test will show, in a general way, the probable effect of surges, lightning, etc., on the life of the insulator, as well as uniformity of the porcelain. The number of strokes, and voltage, to puncture, will depend upon wave front of impulse, or frequency, etc. This cannot now be definitely specified, as the phenomena have not yet been sufficiently investigated. A test as above, however, is very important in competitive tests.

32. *Rain Tests—Position of Insulator:*

With pin insulators, where more convenient, instead of inclining the spray at 45 deg. with the insulator, the latter being vertical,—the spray may be made vertical and the insulator inclined at 45 deg.

Discussion on "Suggested Specifications for Testing High-Voltage Insulators" (Peek, Sandford and Thomas), Cooperstown, New York, June 25, 1913.

F. W. Peek, Jr.: The line insulator is an important factor in determining the success or failure of a transmission scheme. The requirements in present insulator specifications in no way provide for uniform porcelain. Destructive puncture tests are generally made on a few selected units which may indicate a very good insulator. On account of the great lack of uniformity in most porcelain these tests do not determine the performance of the bulk of the insulators which are manufactured later and put on the line. It is thus seen that uniformity of the porcelain is one of the most desirable features of a line insulator. I should like to bring out a few points that should be covered. In almost all other engineering work the strength of a given material is known and can be depended upon within a small per cent of the value indicated by test pieces. The material is uniform, and uniformity is a necessity. If structural steel varied a tenth as much as most porcelain used in present line insulators, there could be no "sky scrapers." Tests, then, should be such as to secure uniform porcelain. This might be accomplished by requiring the destructive uniformity test, or the impulse test, made on insulators taken at random from different parts of the kiln at each firing. Again, the specifications might require that a certain percentage of the insulators of each kiln at each firing pass the factory test, otherwise *all the insulators of the kiln* at the given firing be condemned. For instance—if in one firing in a given kiln 50 per cent of the insulators fail to pass the factory test, and if in the next firing only 10 per cent fail to pass the factory test, the insulators in firing No. 2 would be much more reliable. A greater percentage would stand voltage rises on the line.

I do not believe that the factory tests made on all of the insulators should be too severe. For example, an exceedingly high voltage of steep wave front, or short duration, may be impressed upon an insulator without any apparent damage, but nevertheless the insulator is weakened. It may be that after nine of such applications there is no visible change but on the tenth application puncture may occur.

This is probably one reason why insulators that have long given good service after a time begin to break down, by the weakening due to accumulative effect of impulses received in service caused by arcing grounds, arcing over of poor insulators, lighting, etc.

It is desirable to make such tests, but only on insulators that are not to be used on the line. These tests indicate what can be expected of the bulk of the insulators if the porcelain is uniform.

Some suspension insulators recently came to my attention which had passed factory inspection. These would ordinarily have been placed in service. On breaking a few it was seen

that the porcelain was very porous. Such insulators puncture at very low voltage when dry, and when the glaze becomes checked, breakdown will generally occur in practise. Moisture is undesirable in the cement even when the porcelain is good. Cases have come to my attention where, due to the cement and moisture, the metal pin was chemically affected. A coating formed on the pin. The pin, thus increased in size, placed the porcelain under great mechanical stress, probably producing tiny cracks. When puncture occurred in such insulators due to lightning, even when dynamic was not on the line, the cap was ruptured as in a boiler explosion, dropping the line to the ground. The explosion was probably caused by sudden expansion of moisture in the cement. The mechanical stress and tiny cracks therefrom weakened the insulator so that puncture also took place at line voltage. Moisture-proof cement seems desirable.

It is very important that when arc-over occurs, the design should be such that it takes place completely around the string and not from unit to unit in cascade. Complete arc-over is most likely to be obtained if the voltage balance of the string is good. When arc-over takes place in cascade the equivalent of successive impulse tests are played on the units as the arc approaches the tower unit, until finally, when the tower unit is reached, the full line voltage or over will be on this unit until it arcs over or punctures. A cascade arc also heats the units more than a complete arc, and breakage due to heat, and hence dropping of the line, is likely to occur.

It is not often realized that altitude makes a vast difference in arc-over voltage of insulators.

In making insulator tests, the transformer ratio should be calibrated with the sphere gap to include wave shape. Voltage may then be measured by ratio if the same method of voltage control is used.

In all engineering work the cost of various factors must be so divided that a maximum return is obtained from the investment. Engineers should realize that it is better to pay more at the start for a good and wisely selected insulator than to pay many times later by the loss of prestige due to poor service, and by damaged apparatus, to say nothing of the replacement of insulators. Each insulator that punctures or arcs over sends out impulses of high frequency which may weaken or destroy other insulators and apparatus.

While good uniform porcelain is necessary, it must be remembered that good porcelain does not always mean a good insulator, that good insulators may be weakened by improperly adding perfectly good porcelain.

My "Suggested Specifications" do not require an ideal insulator, but are requirements which I believe can be met at the present time by any manufacturer at reasonable cost. The suggestions are given not so much to make fixed specifications,

but rather to bring out points not often realized. It is to be hoped that it will not be long before insulators are designed with due regard to the dielectric circuit, and that porcelain is either superseded or becomes a uniform dependable product.

J. A. Sandford, Jr.: In looking over these specifications with the criticisms, from the insulator manufacturers' standpoint, I would like to have you look at them as much as possible from the standpoint of specifications written to cover the requirements which are necessary in order to produce a good quality of insulator, and not so much a specification to cover the design of the insulator which the purchaser may choose. Undoubtedly, a set of specifications which the purchasing engineer writes must include paragraphs covering certain points that will govern the design, or performance tests, you might say, of the insulator completely made up.

It would seem to me as though, if it were possible to do so, it would be well if all specifications for tests that are required to demonstrate the performance of an insulator could be written up and isolated from the tests that are required to demonstrate the quality of the porcelain in the insulator to show that good insulators are being shipped. The reason I say that is this: After the insulator has been decided upon and the contract has been signed, the greatest thing that has to be contended with, very often, is the judgment of the man sent to the factory to select the individual units for insulators out of the lot put before him. For this reason it is advisable to have as few points as possible left to be decided by the inspector. If the purchaser's engineer decides all points concerning design, it will only be necessary for the inspector to see that good material is furnished; that it is according to drawing, and that the proper tests are applied to all units. It seems to me it would be more satisfactory and to the advantage of all concerned if these things could be separated, but that is hardly possible. At the same time, from the factory standpoint, that is the way the specification should be looked at; *i. e.*, simply from the standpoint of producing good insulators of the design already contracted for.

Referring to the paragraph headed "Corona" in Mr. Peek's specifications, I believe I am perfectly safe in saying that there is not a single type of suspension insulator on the market to-day that would not show corona around the metal stud cemented into the under side of the unit, if tested at 1.3 line voltage, assuming this to be 110,000 and the number of units per insulator as seven. I am pretty sure that there are a good many 110,000-volt insulators in use to-day that will show corona at about 65,000 volts. To be sure, it is very slight, but at the same time it is visible, and there again comes up the question of judgment of the man who has these things to decide, as to how much he is going to allow. If you leave the wording in the specification so that it will read "there must be absolutely no sign of corona," prospective purchasers must buy a different

insulator from that which has been used for like conditions in the past with seemingly satisfactory results.

Referring to the pin type of insulators, there is one thing which might have been added which would have read something like this: "In no case is any porcelain part to be tested at less than 70,000 volts." As a matter of fact, we never test any porcelain part ourselves at less than the voltage that the part is designed to stand when assembled as a part of a complete insulator, and we think that is a safe practise.

Now referring further to the pin type specifications, mechanical test, that is stated as a definite figure at 2000 lb. I think that this value would apply all right in all cases for insulators of 25,000 volts or higher. I think possibly, however, that this value should have been left blank, because in the case of some of the smaller insulators, say 10,000 volts, or 11,000 volts, it might be found possible on some designs to approach that figure, but it is my experience in 90 per cent of the cases where we are called upon to apply a certain specification test to the pin type insulator as indicated, that the test usually resolves itself down into a test of the pin, because the pins generally bend at a considerably less load than 2000 lb., and particularly on a 60,000-volt insulator of the largest size.

Referring to the paragraphs headed "Minimum Distance from Insulator to Grounded Objects," and "Number of Insulators to be Tested at One Time," and "Factor of Safety—Dry," etc.; when Mr. Thomas received the first draft of the specifications I submitted to him, he asked me several questions, and these paragraphs might be considered as answers to those questions. In other words, they are the view that the porcelain manufacturers take of these subjects, particularly from the point of producing good quality insulators, not that some of these points might and ought to be included in the performance test, preliminary to the placing of the contract.

Under the heading of "Quality of Water for Rain Test Purposes," the first time I encountered this difficulty was when we were put to it to make a certain suspension type insulator come up to certain requirements under the rain test, and I could not do it with the equipment I had, using everything as it was installed. We had our water from artesian wells, water coming up through several layers of gas beds, coal fields, etc., so in order to take up the problem and solve it we took the identical insulator disks tested in our own factory, the spraying outfit and everything that was movable, and transported them to Pittsfield, Mass., and we made another test there. The results were rather startling. We then took the specific resistance of the water; the first (Lisbon) water was 880 ohms, and the second (Pittsfield) water was 7000 ohms. Later we installed in our factory for this kind of work a little half-inch steam trap and tank to collect water from our heater system, and let the water cool down and used this water for similar testing

purposes. The specific resistance of this water was 30,000 ohms. I have the apparatus so arranged that I can turn one valve for one water and another valve for the other water, and the difference will run as high as 40 per cent.

I think the specification that has been written by Mr. Thomas, with those points left blank, so far as the actual value is concerned, is a good one, and as I stated here, in my report, this method of obtaining a good water may be put in practise. I think this apparatus could very likely be installed at any place where the test was likely to be made.

Referring to the dew test, from our standpoint it does not show anything in the performance of the insulator over what can be obtained in other ways. In the winter time I believe we can get a better test than any dew test would be by simply hanging the insulators out of doors and bringing them indoors and applying the test immediately. In this way you get a coating of moisture over the insulator which is better than that put on by steam or any other method.

The question of the capacity of the equipment is a thing which seems to be more or less a bone of contention. It is oftentimes specified, but often winds up, and probably has to wind up, by the engineer accepting what he finds at the manufacturer's plant at which it seems most advantageous to him to place his order. I think in nearly every case all the insulator manufacturers have a good equipment, and it seems to me that so far as any routine factory tests are concerned, that it need not be thought of in the specification. If there are any special performance tests where very careful note is to be taken of small variations in the performance of the insulator, then it is well to specify the various conditions, and among others the capacity of the equipment; but generally tests of that kind are made in a laboratory which has at its disposal various capacities of equipment and therefore such specifications may be admissible.

Now the method of controlling the voltage is subject to about the same limitations; that is, the potentiometer method, I believe, is good, but you realize the manufacturer is cutting down his costs just as far as he can for the factory tests and the potentiometer method of making the test will be very expensive. Take for instance a porcelain plant. Either one of our plants is probably as large as any other one plant in the business, and even at that we only require about an average of 80 h.p. to drive the whole factory. If you are going to load up a considerable per cent of that by using up power in water resistance, the people who are paying the bills will object, and I can see no reason why that should be necessary, except, again, in cases where performance tests are being made and a careful note has to be made of small differences, in which case it looks to me like a laboratory proposition and should be so treated.

You can see I am looking at this purely from the standpoint

of the quality of the porcelain; therefore the grounding of one end or the middle of the test circuit goes along the same line except that for convenience it is very much easier for us to use the middle point grounded, on account of the fact that we have only to insulate through the buildings at half potential. We were compelled to put up sprinkler systems everywhere, and the less voltage we have to insulate in the factory the better off we are.

In regard to the paragraph concerning the breakdown of the insulator. Generally the breaking down of an insulator means the total destruction of that insulator, and if it would be consistent, I think it would be well to have that so understood.

The corona discharge, etc., is often specified, and with reference to what Mr. Peek says, that there shall be "absolutely no corona," if we make a performance test at our factory, or at some other factory, or at some neutral point, and along comes an inspector and we make another test, and in his judgment the above specification is not fulfilled, what is going to be the answer? It seems to me the items I have taken up in that last paragraph on page 1469 and the paragraph at the top of page 1470 should be wholly and finally decided before the contract is signed and then remain as decided, because you cannot change the insulator afterwards. I have seen strings of insulators sometimes, among which, right along in the same string, there will be one unit absolutely dark between two units that show considerable corona.

As to the test for the puncture strength of the insulator, such test to be made under oil, I think this test is a very good thing. I cannot quite agree with Mr. Thomas, however, as to the method of raising the voltage by a thousand volts a minute, or whatever other time might be adopted, because ordinarily the factory equipment at an insulator factory is not calibrated, the low-voltage meters which they have are not calibrated so that they read directly in kilovolts on the high-tension side. I rather like the method which I suggest here in the last part of this section. I used the old method myself at one time, but since then I have had a considerable amount of experience in applying the voltage in this way and I may say it works out very well indeed and will show up results as well as or better than any other method I ever tried for testing under oil.

As to the last paragraph, there is not anything better that I know of that can be said on that than to look at Mr. Nicholson's paper for this part of the discussion. First of all it is a design test, and it is difficult to apply because ordinarily the mechanical testing equipment in the factory may or may not be anywhere near the electrical equipment, and it means there must be provided special arrangements, etc., for rigging it up. But there are one or two things which Mr. Nicholson says here, which, if they are substantiated by more tests later, it would seem to me would justify by good proof our taking the stand that I have indicated in this last paragraph, viz., in eliminating such a test,

because you will see in Mr. Nicholson's discussion that he says: "In our effort to explain these results, mechanical loads were applied to insulator disks and then removed, voltage being applied after the removal of the loads. In other words, the electrical test followed the mechanical test. Almost identical results were obtained by this method as in the simultaneous electrical and mechanical tests. This fact seems to indicate that puncture occurs by reason of injury to the porcelain by the mechanical load, rather than by a combination of mechanical and electrical stresses acting simultaneously." If that proved true, in more extended experiments—we have not done much on it ourselves—I see no reason why then we should not apply a routine test to all units, which we do now. We may have to raise that a little and then apply our flash-over test with a definite time-limit rather than an instantaneous test, I think, and accomplish just as good results; in fact better, I believe, than by trying to determine the result from using the simultaneous test.

Further on Mr. Nicholson says, "Moreover, it is noteworthy that usually an insulator during or after a mechanical load which caused puncture, would withstand flash-over voltage for several seconds' time before puncture occurred. These observations indicate that mechanical loads insufficient to actually crack the porcelain may overstrain it to a point where its dielectric strength is greatly reduced." I do not know, but I think that if all the insulators that were put to that test were of uniform vitrification, this difference would not exist; in other words, if the insulator was damaged at all, it was punctured practically instantaneously with the final voltage. It seems to me if that condition is going to exist, the thing I spoke of a short time ago should be introduced and I have written this down as an addition to that statement: "If this condition is found to prevail after more numerous data have shown such to be the case, the final electrical tests after the mechanical pull should be for a definite length of time, not for the so-called 'instantaneous' application."

I think if that condition exists, a test, perhaps one of two minutes, or whatever may be thought to be a proper time element, would weed out any such cases.

What we would like to see would be a set of specifications drawn up that will not put any more fussy testing and experimental work than necessary up to the manufacturer after the contract is signed. It seems to me all these things should be determined beforehand and that afterwards all there is to be done is to be sure that each and every insulator and each and every piece of porcelain of a completed insulator, in the case of the pin type insulator, is perfect or as nearly perfect as we can make it. It makes it easier for the inspector, the manufacturer and the purchaser, and the purchaser will get just as good material in the end.

P. H. Thomas: I will take a few minutes to call attention to certain parts of the third specification, the one drawn up to

embody what seemed to be the best and most practical features of the specifications which you have just heard discussed.

On page 1472, section 6, I have suggested a factor of safety for testing on metal parts. I do not believe such a requirement has been usually made, and I do not suppose it is necessary to put very much stress upon it, but it gives a criterion for the guidance of the man who is designing the mechanical parts.

On page 1473, paragraph 9, reference is made to the absorption of moisture by the porcelain. This is taken from Mr. Peek's specification, and is, I think, a very important feature. Personally I am inclined to believe that the amount of absorption is a very good measure of the density and quality of the porcelain. I would call the attention particularly of the manufacturers to the question as to whether they feel that this value given in paragraph 9 can be reasonably and reliably attained. Mr. Peek gives an absorption of not more than 0.25 per cent, and Mr. Sandford, in his case, gives 0.1 of 1 per cent, with a differently worded method of making the test. I have put in Mr. Sandford's figures in the specification, and ask that this point be discussed. One-tenth of 1 per cent may be too severe a requirement.

At the bottom of the page you will notice that I have made a careful distinction between routine tests and design tests. This is in line with the request of Mr. Sandford that when we have once decided on the design then it remains to make tests on individual units which shall insure that the insulators reasonably correspond to these designs. All that is required for the routine tests is that once in a while the method used for the routine test be calibrated by the prescribed method of making tests, and any reasonable method of checking up the voltage as shown on the test can be used. That gives the manufacturers an opportunity of using any apparatus which they may have available, provided it is reasonably good, for handling their factory output.

Paragraph 16, with relation to frequency, is a compromise. Ideally, we should test every insulator on the frequency at which it is to be operated, but it is a hardship on the manufacturers to require testing at the various commercial frequencies. I am inclined to think that in ordinary cases a 60-cycle test would show pretty nearly the same results as 100-cycle or 125-cycle test, up to 40,000 volts, provided the other conditions were as specified. The variations between frequencies in testing are due to many other things than differences in frequency, such as differences in the characteristics of transformers, the characteristics of the generators and the methods of the application of a voltage.

The next paragraph, on "what constitutes a breakdown," is perhaps the first definite injection of such matter into a specification. This paragraph comes from Mr. Sandford's specification.

The oil tests, it seems to me, are absolutely necessary in important lines. How large a percentage over the flash-over voltage shall be required for the test under oil for the puncture

test is open to debate. It is given as 125 per cent in this specification.

As to paragraph 22, in reference to mechanical tests on pin insulators. I would like to read the last sentence. This is a novel statement, and whether it will be approved or not I do not know. It is as follows: "In case of failure the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load." In my opinion it is not sufficient to put in a perfectly good pin to find whether the insulator will stand the overload, but the pin which is used should be one which will not bend or spring in service, so it seems to me worth while to make the test on the design with the pin you are going to use.

Paragraph 25, and other paragraphs in this group, refer to routine testing. The question is as to how long these tests shall be continued, and that is one of very considerable practical importance. When you are making a test of one thousand insulators, it makes a difference whether every one must be tested one minute or five minutes.

I would call on Mr. Nicholson to read the contribution which he has made, which contribution has been printed, and which describes some of his tests on a simultaneous application of electrical and mechanical stresses. I consider this a very important matter, and I would like to have it called to your attention at this particular point in the consideration of these specifications.

L. C. Nicholson: A series of tests, not yet completed, has been undertaken to determine the performance of suspension type insulators when subjected simultaneously to electrical and mechanical stress.

We find that mechanical loads do not affect the flash-over value of the insulators, but do affect the puncture or dielectric strength. A load much less than that necessary to cause apparent mechanical failure induces puncture at dry flash-over voltage. Thus, insulators having an ultimate mechanical value of 9000 to 12,000 lb. (4080 to 5440 kg.) will puncture when subjected to from 4000 to 9000 lb. (1815 to 4080 kg.) pull and dry flash-over voltage simultaneously.

Mechanical load was applied by means of an overhead hand crane, three insulator disks in series being anchored to floor. Voltage was obtained from a 50-kw., 25-cycle, 250,000-volt testing transformer, regulation being effected by a water rheostat.

Expressed in per cent of the number of disks tested under ascending mechanical loads we find that:

5	per	cent	puncture	at	4000 lb. (1815 kg.) pull.			
8	"	"	"	"	or	below	5000 lb.	(2270 kg.) pull.
22	"	"	"	"	"	"	6000 lb.	(2720 kg.) pull.
50	"	"	"	"	"	"	7000 lb.	(3175 kg.) "
90	"	"	"	"	"	"	8000 lb.	(3630 kg.) "
100	"	"	"	"	"	"	9000 lb.	(4080 kg.) "

Several types of insulators from several different manufacturers were experimented with. No marked difference between the different kinds was found to exist, with perhaps one exception. This was a "strain type" insulator with extra heavy metal parts. Only a few of these were available, but none of those tested punctured at a load of less than 8000 lb. (3630 kg.), and some of them withstood 10,000 lb. (4540 kg.) successfully. The ultimate strength of this insulator was from 10,000 to 12,000 lb. (4540 to 5440 kg.).

In our effort to explain these results, mechanical loads were applied to insulator disks and then removed, voltage being applied after the removal of the loads. In other words, the electrical test followed the mechanical test. Almost identical results were obtained by this method as in the simultaneous electrical and mechanical tests. This fact seems to indicate that puncture occurs by reason of injury to the porcelain by the mechanical load, rather than by a combination of mechanical and electrical stresses acting simultaneously.

Usually, though not always, puncture occurred previous to any audible noise from the insulator, such as would indicate crushing or cracking of the porcelain. Moreover, it is noteworthy that usually an insulator during or after a mechanical load which caused puncture would withstand flash-over voltage for several seconds' time before puncture occurred. These observations indicate that mechanical loads insufficient to actually crack the porcelain may overstrain it to a point where its dielectric strength is greatly reduced.

We believe the shape of metal parts, as well as the size, shape and distribution of grooves in the porcelain, are important factors in this matter. Undoubtedly other factors and effects are present, and the subject is one deserving careful study and investigation.

As to the theory of what happens I am not able to say. I have simply pointed out in my discussion the results which are obtained.

There is not much audible noise. In many cases the insulator will hold the voltage for 30 seconds before it punctures, indicating that the material may have been strained, although not actually cracked. This factor varies with different shapes of hardware and different shapes of porcelain, depth of grooves, distribution of grooves and all that sort of thing. I have not begun to find out the nature or extent of the phenomenon.

P. H. Thomas: You can see this work of Mr. Nicholson was a serious matter. There are in service a great many strain insulators of the type tested, and much difficulty is experienced with them in the respect indicated. Our specifications ought to protect us against it. At the present time we do not have data enough to conclude just the significance of this feature which Mr. Nicholson points out. It may be that further experiments will show that the weakening of the dielectric by mechanical stress is an extremely common occurrence.

We are especially interested in what the cause of the trouble is and what is the nature of the action. It is a speculation at the present time, but the thought must occur to us that there is a mechanical deformation of the parts which are under a strain approximating the elastic limit. We have metal parts, porcelain parts, and cement parts, and under the strain there must be a certain amount of mechanical change of shape. Porcelain is a brittle substance and it is possible there are tension strains developed in it which will cause not a clear crack, but an opening up of the material which allows a little penetration of charge. This speculation is supported by one of the comments of Mr. Nicholson that there was one set of disks which did not act as badly as the others and that this set had excessively heavy mechanical parts. If it is true that distortion is the cause of the difficulty, it can be corrected.

I think we have done all we can in these specifications to forestall the effect of mechanical stress in calling for the making of the electrical routine test after the mechanical test. Mr. Nicholson's study as far as it goes, shows the test is no more severe made at the time of the mechanical test than it is afterwards.

I hope that all engineers interested will make full criticism of these proposed specifications.

H. W. Crozier: What has become of the idea that each unit in a string of insulators should be able to stand the line potential? That idea was advanced some time ago, that is, that each unit should be able to stand, as a puncture test, the line voltage.

I want to add a word of caution in regard to the mechanical tests proposed. Mr. Nicholson's discussion particularly brings this out. In a good deal of work which we did, samples of the insulators were tested to destruction. In our practical insulator work we are not testing samples, but we are testing actual insulators, and we must take care we do not do things to the insulator in our testing which will reduce their efficiency. We may take strain insulators capable of standing 15,000 lb., and we can easily realize from Mr. Nicholson's discussion that if we overload these insulators we greatly reduce their resistance to electrical puncture. If we take all the insulators of a line and apply a severe mechanical test to them, we have reduced the resistance to puncture of the whole number of insulators by a margin of forty or fifty per cent. We will have to test a lot of insulators mechanically to provide for strain insulators, but for the other insulators, which are going to act as supporting insulators and throughout their life may not be called upon to support more than a few hundred pounds, it would be desirable to omit the mechanical test altogether.

P. H. Thomas: Has Mr. Peek, or Mr. Sandford, anything to say about making each unit in the string stand the line potential? That would seem obviously impracticable when you have high voltages. It might be practicable in some cases, but if you have seven or eight insulators in a string, it would be impracticable, in my opinion.

J. A. Sandford, Jr.: If Mr. Crozier adds under oil, there is no insulator made today that will not stand the line potential under oil.

H. Koganei: With regard to the oil test of insulators, I made a series of tests and observed some phenomena which are not yet well explained. The insulators tested were all of pin type for working voltages of 15,000, 25,000 and 35,000 volts. At first I made the arc-over test with three times working voltages for five minutes. Then selecting ten insulators from each size which arced over without puncturing, I immersed them in oil to make the puncture tests. The puncture voltages varied from 80 to 90 per cent of the arc-over voltages.

It seems quite reasonable to show lower puncture voltage in oil due to the concentration of the dielectric field near the terminals. To eliminate this effect of the field distribution, I selected another lot of ten insulators from each size and pasted tin foil on the top and the pin hole. Even in this case they were all punctured at the same voltages near the center of the electrodes and none at the edges.

The voltage was measured by the needle gap, which checked very well with the voltage calculated from the turn ratio. The voltage was increased at the rate of 1000 volts per minute.

The flux distribution in the latter case, near the puncturing point, may be considered to be more uniform than in the arc-over test. Nevertheless, the insulators were punctured in the oil at least 10 to 20 per cent lower voltage than they will puncture in the air. Unfortunately, these tests were made just before I started from Japan and I did not have enough time to get any further result. The insulators were made in Japan.

F. W. Peek, Jr.: The suspension insulator as a rule does not act in that way under oil. The only explanation would be some local concentration of flux due to the oil, and with the suspension type, the breakdown under oil always takes place between pin and cap where the oil can in no appreciable way affect the flux distribution. The flux distribution would be affected in the pin type insulator. I do not think the oil has any peculiar effect.

M. T. Crawford: Mr. Sandford recommends the wet flash-over voltage test for pin type insulators to be not less than 175 per cent of the operating voltage. My experience has been that not less than 200 per cent normal voltage is a better minimum, or possibly 225 per cent as recommended by Mr. Peek. I have also found it to advantage to have each insulator marked with an identifying stamp by the inspector, so that none are skipped in the test by mistake during a rush delivery. On one job of over 30,000 insulators tested in this way to over 200 per cent normal voltage. There have been practically no failures in four years' service, whereas another job with a less rigid test has given a considerable number of failures, although they have identically the same design and are used under the

same operating conditions. In this case the greater cost of the insulators tested with the higher pressure was more than warranted.

P. H. Thomas: In regard to the propriety of omitting the mechanical test on insulators which are not to be used as strain insulators, something may be said both ways. In the third specification, paragraph 22, page 1476, a blank is left for the value of the pull test. If it is desired, insulators can be made in two classes, one to receive a test commensurate with the ordinary strain of the line insulator, and the other for the high strain of the strain insulators; since by the breaking of a conductor a high mechanical strain is likely to be brought on a suspension insulator, it seems to me it would be, as a matter of fact, and of practical wisdom, dangerous to try to use a suspension insulator that would not stand the strain of a broken conductor.

J. A. Sandford, Jr.: It seems to me the strain insulator is the one to stand the load. If there is any damage done by applying the mechanical stress, that is the one to receive the stress, and it should not be received by the span insulators.

L. C. Nicholson: Insulators intended for service should not be damaged by mechanical or other tests, but it is evidently unwise to place an insulator in service subject to a certain mechanical load which has not been actually tested somewhat in excess of the loading it will receive under actual operating conditions. If there is any question as to the ability of the insulator to carry this load, two or more insulator strings should be used in parallel.

There has been considerable trouble with strain insulators on transmission lines. This has been attributed by some to too high mechanical loading, and by others to the self-induction or choke coil effect of the conductor loop as usually employed at angle or dead-end towers. No one seems to have any definite explanation of what is responsible for strain insulator trouble. The mechanical-electrical tests cited show that dead-end insulators may be weakened electrically by mechanical loading. Furthermore, these tests were of short duration, and do not tell us what effect would come from alternate loading and unloading over long periods of time such as occur in practise.

In addition to mechanical loads, internal stresses of considerable magnitude are induced by atmospheric temperature changes. In a paper by Mr. Austin before the National Electric Light Association, at Chicago, it was shown that a stress of at least 400 lb. per sq. in. may be induced. Since this value is practically one-half the ultimate strength of the porcelain, it appears that medium mechanical loading in combination with temperature effects may in time result disastrously to the insulator.

These considerations indicate that the shape of suspension insulators may be changed to advantage—better to withstand loads and temperature changes. Are we not making an error

in the construction of the insulator in confining a small knob of porcelain in a perfectly rigid iron pocket? Or, would not some substance other than cement, which would be more elastic, be better in this respect?

In general, the points mentioned in the specifications under discussion are good, but I believe they do not go far enough. There are a number of important things about insulators which we do not know, and which we appear perfectly content to leave to the manufacturers, without making an effort to find out about them. The manufacturers are in general reliable and honest, but have not so far sufficiently distinguished the technique of insulator design from the commercial production of insulators. Electrical engineers are willing to leave these matters entirely in the hands of the manufacturer, and depend upon final test and inspection to secure satisfactory insulators. For example, we never ask any questions nor make any requirements relating to the composition of insulators we intend to use. We leave the entire ceramics of the matter absolutely in others' hands, and have made no efforts to study intelligently the composition or firing of the porcelain. In a matter so important to the electrical industry, I feel that the American Institute of Electrical Engineers or some other body should undertake to become familiar with insulator production, to the extent that specifications may be prepared covering not only the testing, but the composition and production of insulators.

The point raised by Mr. Peek concerning proper spacing of units to prevent flash-over in cascade, is in my experience of slight practical importance. With the usual spacing of units, when dry the string flashes over, but when wet the units flash over individually. Since the wet condition is the practical one, I fail to see any advantage to be derived from a close application of the theory based on dry flash-over.

C. O. Mailloux: I would like to say a few words about going into the mixing room too early. I have had some experience in cases where it was necessary for the consulting engineer to decide whether there was to be or was not to be a mixing room. I have found it to be true in electrical engineering, and in all other professions, that the shoemaker should stick to his last. I think it is dangerous for the electrical engineer who has not made a thorough study of ceramics, at least as thorough as the ceramic expert himself, to go into the mixing room and tell the ceramic manufacturer what to do. There is a parallel case in the manufacture of insulation for wires. I have found that in undertaking to tell the manufacturer of insulation for wire, how to manufacture and how to apply the insulation, one was liable to hamper the operation most seriously and make difficulties which not only tended to, and actually did, increase the cost of the output, but also decreased its insulating and lasting qualities. Hence, in my opinion, it is quite as well to

let the ceramic expert confine himself to that specialty. I do not care how strongly we insist on the *results*, but when it comes to the methods of accomplishing these results, I think we should leave to the manufacturer the widest possible latitude.

Paul M. Lincoln: Concerning the quality of water which is recommended for making the rain test, I have run across a good many different kinds of water, and I find there is a tremendous variation so far as their electrical resistance goes. Some water is a fairly good conductor and some is a pretty good insulator. It seems to me Mr. Sandford is quite logical in suggesting in his specifications that the water which is used for rain tests in testing insulators shall be condensed steam, for the reason that the water which wets the insulator in practise is of the same nature, viz: rain-water, and it is practically pure. The only opportunity it has for gathering up impurities is in the course of its descent through the air, and while it may take up a very small percentage of impurity from the air I do not believe that is sufficient to make its character very different from that of the condensed steam which Mr. Sandford suggests.

Another point is one in which I cannot agree with Mr. Sandford. He suggests that the connection of the transformer which shall be used for testing—whether it be grounded in the middle or at one end—shall be at the manufacturer's convenience. I know from my own experience that there is a tremendous difference between these two methods of connection. It is on account of the disposition of the static field around the insulators.

Insulators, when used, have the pins grounded, and I believe the test should be made under the same conditions, as nearly as possible, and I therefore believe the specification for testing insulators should carry with it the condition that the pin of the insulator shall be grounded during the test.

Percy H. Thomas: We meet both conditions in some specifications. The design test is made on the nearest approximation test to the service conditions, and for the routine factory output the test conforms to the calibration of the low-voltage voltmeter, with the result that we approximate the actual conditions, and make the output test with the easier apparatus.

A Member: I would add a little to what Mr. Mailloux said about the danger of going into the mixing room, and I will refer to some experiences I was familiar with, in which one body of engineers, in making a report, stated that they had told the manufacturer not only what to put in the mixture for the insulation, but how to put the insulation on the wire also.

In any consideration of the subject of the composition of mixtures of any kind, and their application, we must realize that improvements are being made all the time and that any specific directions which an electrical engineer might give on this subject would not hold for very long.

Hugh T. Wreaks: Referring to the point brought out by Mr. Sandford about the question of packing, this seems to me very important. In specifications of many other kinds of material, specific attention is given to how the material should be packed. We have had occasion to note damage in shipment of insulators, and even in cases where the penalty for breakage came on the manufacturer, a good many were damaged in shipment.

Judging from experiments of Mr. Nicholson, it seems to me not unlikely that many insulators may be strained in shipment, with consequent weakness developing in the field, the fault in this case being due, not to how insulators were manufactured, but to how they were packed and handled in shipment.

E. E. F. Creighton: The endeavor to standardize the tests on insulators is, I think, a valuable move in the right direction. Even if the rules are not adopted, they will have their value. Although it is impossible to get any information at the present time on the proper manufacture of porcelain and therefore it cannot be included in these rules, yet this is one of the most important features regarding the insulators. Sooner or later some one must make a careful investigation, for the information of electrical engineers, of the following factors:

First. The effects of each of the ingredients that go into porcelain.

Second. The proper deposition and drying of this material without allowing flaws to be formed in the body of the material.

Third. The proper temperature and proper length of time of firing for proper vitrification.

There is little practical use in stating that porcelain should be properly vitrified unless some specific directions can be given. The absorption of water by porcelain has been used as a rough test of the degree of vitrification but the method is unsatisfactory in several respects, especially in the fact that it requires the destruction of an insulator. From the experiments I have made I think it is possible to develop some other method which will be not only more satisfactory but will leave the insulator intact after testing.

Along a different line of endeavor some experiments made on clays relating to vitrification, are apropos to the problems of porcelain manufacture.

Our tests were made on the vitrification of clays, using as a basis of vitrification the stability of the material as a resistance; at 1200 degrees there was very little vitrification; at 1300 degrees vitrification was fairly started; and at 1350 degrees complete vitrification took place, although as high a temperature as 1500 degrees was used at times to advantage, for the particular work in hand.

Another test made in vitrification was relative to the time of heating. The material was heated successively for periods of about one-half hour and measurements were taken after each heating. The curve showing the general relations is given in the accompany-

ing Fig. 1. The degree of vitrification is represented by the conductivity. In the curve the reciprocal of conductivity, namely resistance, is given. These curves of time versus vitrification vary in form according to the temperature used. Naturally, the higher the temperature, the more rapid the vitrification.

Although these tests were not made directly on porcelain for insulating purposes, it seems that they would show the necessity of scientific work being done in the manufacture of porcelain. Until this work is done results will vary tremendously.

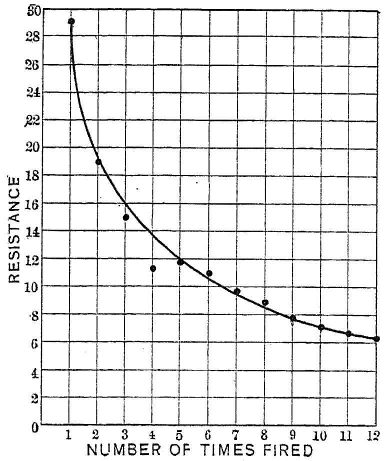


FIG. 1

This curve shows the relative degree of vitrification of clay by the decrease in ohmic resistance. The duration of each firing was approximately one-half hour. The last few tests showed almost constant resistance, which we presume indicates the final condition of vitrification for the particular temperature used, namely, about 1400 deg. cent.

In all other forms of insulation the manufacturer aims never to test the insulation to anywhere near its complete dielectric strength. Destructive tests are made on samples of material, and the methods of manufacture are regulated to keep the product uniform. With the methods of manufacture fixed, a factor of safety is taken on the dielectric strength of this material and is then not strained above the danger zone. Finally, it would seem that this would be the proper way to take care of the manufacture of porcelain insulators. If the proper chemicals are chosen in the first place and the material is properly worked and properly fired, it will be necessary only to test it in such a way as to get rid of evident flaws. In the past there has been turned out a considerable quantity of imperfectly vitrified porcelain, and this is liable to be damaged by the tests which are made to discover the flaws.

In testing for flaws, it has been found that the high-frequency currents from an oscillating transformer produce a general stress over the whole surface of the insulator, each successive spark traveling over new surface of the porcelain skirts. Still further, we have found that by limiting the potential of the oscillating transformer, the strain on the porcelain can apparently be made even less than on the 60-cycle test. This is due to the fact that the higher frequency favors the production of creeping sparks along the surface. With the same applied potential the creeping spark will extend farther as the frequency increases. At the same time, the dielectric losses in the porcelain will increase as the frequency increases. Herein are the relations

which should be carefully studied. There is an evident probability that a high-frequency test can be made which will not strain good porcelain but which will tend to develop and pick out accidental flaws in the material.

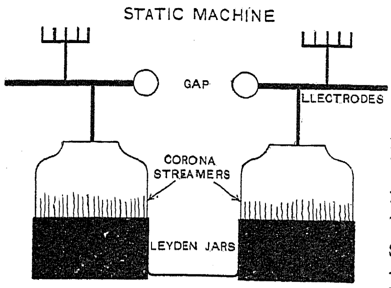


FIG. 2

In the foregoing criticisms it is evident that we have started from the point where the electrical engineering leaves off, namely the point of design; it has been stated many times that an insulator should be so designed that it will spark around the skirts rather than puncture the porcelain.

I want to emphasize a point brought out by Mr. Thomas in his remarks relative to the frequency at which the insulator is to be used. Actually, when you consider the use of the insulator, it is never over-strained at 60 cycles or 25 cycles. It is strained by lightning frequencies and by the frequencies that occur through accidental arcing grounds, and it is for that reason I think that all testing should be done with high frequency. The failures of insulators, outside of the effects of mechanical strains, can be attributed entirely to lightning and arcing grounds.

Some potential tests made a few years ago with panes of glass in air and in oil seem to answer the question of Mr. Koganei. If an ordinary piece of window glass in the air with the electrodes on the outside of it, is subjected to potential stresses, it is possible to raise the potential to a higher point than if it is immersed in oil. We made a series of tests to determine the reason for this and came to the conclusion that it was not due to the distribution of potential around the electrodes, but was due to the safety-valve effect of the corona streamers that run along the surface of the glass in air but not when it is immersed in oil.

Consider the ordinary conditions in a disruptive curcuit as shown in Fig. 2. The potential is built up by direct current until the gap is bridged and then the oscillation takes place in this circuit. At the instant of disruptive discharge there will be seen on the surface of the glass jars a tremendous number of little streamers which emanate from the metal covering. These little streamers are the relief valves that protect the glass from puncturing.

If the jars are immersed in oil and filled with oil, the corona streamers are almost entirely suppressed and a puncture of the glass will take place for a smaller gap setting than when the glass is surrounded by air. The corona itself forms extra surface, adding to the electrostatic capacity of the jars. Any sudden local surge thus relieves itself by creating a larger capacity and thus lessening the potential that would otherwise occur accord-

ing to the fundamental law $E = \frac{Q}{C}$. When the corona is suppressed there is no relief valve and consequently a local surge will hammer harder on particular spots in the glass; the extra strain will cause a puncture.

The indications of the existence of local electrical surges over the surfaces of condensers are not lacking. One might as well expect a bucket of water thrown into a trough to produce no splashing as to expect the electric stresses under disruptive discharge to gently and smoothly distribute themselves immediately in the condenser. As an experimental proof of the existence of local surges the following facts are given. When only one leyden jar on each side is used as shown in Fig. 2, a much larger gap can be made to spark without puncturing the glass than if many are used on each side. It was determined that this effect was not due to weakness of several of the many jars used.

Ralph D. Mershon: It seems to me that a question that has been raised before should be emphasized a little more, that is, as to the object of such specifications as these. These are specifications under which insulators are to be purchased from the manufacturer, unde which he is to supply them. Then it seems to me, as pointed out by Mr. Sandford, that all the questions of designs, form of insulation, flash-over, and that sort of thing should be determined before the contract is let, and then forgotten. That is a matter which we cannot usually specify, it seems to me. Our object in preparing any specification, and recommending one, if we are to recommend one, is not to enable engineering work to be automatically done, but these specifications are prepared and are to be used as a guide in procuring any given product determined on.

The preliminary determination as to design and the characteristics that will be given presumably to all the units is one that should depend upon the judgment of the engineer. If it were possible to determine all the characteristics, then it would not be necessary to have any tests at all, perhaps, or any specifications except some rough ones of a general nature, but it is not possible to determine in advance all the characteristics. You cannot lay down a hard and fast rule for the puncturing of the insulators, for instance, in the matter of test under oil, so that it is necessary to draw up specifications which will bring about the production of an article along commercial lines and in very reasonable approximation to the kind of product we are after.

Closely connected with that is the proposition made by Mr. Nicholson in regard to going into the ceramics of the matter. My advice in that connection would be general. I have made a little study of the side of this subject which relates to ceramics, and my experience so far has been that the more deeply you study it the less you know. You will find that the art of ceramics today is hardly on an engineering basis. It is approaching that,

and we have ceramic engineers, but the ceramic engineers meet serious obstacles every once in a while, as I know. There is a suggestion I might make in place of the one which has been made, and that is that we get in touch with our friends, the ceramic engineers, and arrange for some joint meetings on this matter, so that we may both learn something. On our side we will learn something as to the uncertainty of the manufacture of electrical porcelain. I think it is more uncertain than any other material that enters into electrical construction, and our knowledge of it is limited, both in regard to the electrical properties and the mechanical properties. Our knowledge of the mechanical properties is a very indefinite one at the present time. We have but very little information on the tensile strength of porcelain, and such as we have is very conflicting. It depends very greatly not only upon the composition of the porcelain but upon its mechanical treatment during manufacture. For instance, I presume a good many of you would assume that the tensile strength of porcelain, or ceramic material, because some of it is not worthy of the name of porcelain, increased with the vitrification. Now, that is not necessarily the case at all. Some of the strongest objects, that is, strongest with relation to tensile strength, made of ceramic material that I ever tested, have been the most porous and the ones most easily broken by a little knock. I remember one sample of porcelain which was tested up to 2200 lb. per sq.in., which is very high, and someone knocked this piece of porcelain on the floor and it broke into three pieces.

There are a lot of problems which are yet to be solved in regard to ceramic material, both from the chemical, electrical and mechanical side, and it is a pretty complex problem. I think Mr. Mailloux's remarks in that respect were well to the point.

To my mind one of the most important tests is the puncture test under oil, but when you come to apply it and use it as a criterion as to the quality of product, it is extremely difficult to determine how it shall be applied. Mr. Sandford has mentioned the percentage of the product which shall be tested under oil. All right, but suppose you test it under oil and it falls considerably below what you expect it would do, and what the tests of the first samples had encouraged you to believe you would get. What are you going to do about it? Say you have a large order of insulators to be got out on time, and the manufacturer doing the best he can, and his material is considerably below the puncture test you thought you were going to get. It is extremely puzzling to know what to do. You cannot test all of your insulators, that would be almost prohibitive as a matter of course, and few manufacturers have the facilities so that you could test them all under oil. In one case in my own experience we did this—we assumed we could not ask the insulator manufacturer to do any better than it was possible for him to do. The most we could ask then was that we should get as good porcelain as anyone else got. The particular insulators in

question had a lower flash-over value than some others being turned out, so that if they were tested in air they would be tested at a lower voltage as regards puncture than the other insulators being turned out. We could not tell then, from a test in air, as to whether the porcelain in these insulators was as good as that in the others. When we came to make the test under oil, if the puncture values were lower than we thought they ought to be, we agreed that we should have the right to test some of the other product that was going through the factory and which was passing the routine test through air, under oil, and if ours tested out as good as they did, then we were subject to negotiations, even though it was not as good as we thought. If it was not as good as that, we were in the position under the contract to exert some considerable influence. That was agreed upon.

It may be possible to work out some better arrangement, but it is exceedingly puzzling to know how to control your product, when you can only test a small part of it, and when you are dealing with a product which is notoriously non-uniform. On this matter of uniformity I agree with Mr. Peek. I would rather have insulators which run very uniformly in a lot tested, even those in which the puncture value was considerably lower than might be obtained with some other product which was less uniform.

There is one thing Mr. Peek mentioned which I would like to discuss further, and perhaps get some further information on the point, and that is the objection to using the sphere gap in making the insulator tests. He suggests it would be better to calibrate the transformer. I think in many cases it would be, but my reason would be that of convenience. His reason was not quite clear, that was, in making the end test on the insulator the voltage on the spark gap might be higher than otherwise. It seems to me the insulator gets the same voltage as the spark gap does, if the apparatus is properly collected up and located, and I cannot see, from that standpoint, the objection to using the sphere gap.

It seems to me it is important to have the wet and dry tests as nearly the same as possible, so that the idea of specifying the flash-over test dry shall be at least equal to a certain amount seems to me is a little bit irregular. I should say that the most logical way to specify it would be with reference to the wet flash-over test. It seems to me the precipitation in some specifications is pretty high. One inch depth in five minutes would occur to me to be amply high enough for most, if not all, places in the United States. That is considerably higher than the maximum precipitation ever recorded by the U.S. weather bureau. If you want to add a factor of safety, do not add it through the precipitation test. I think it is better to add it through the voltage to be impressed on the insulator. Also in regard to the matter of precipitation, I hope there will be some further discussion on Mr. Thomas's suggestion of inclining the insulator

and using a vertical spray instead of a spray at an angle. It is difficult to get a spray at an angle which will be uniform and accurately directed. It would be much easier to accomplish the same conditions with a vertical spray and the insulator at an angle. The objection may be made that that does not simulate the conditions of practise. In reply to that you can say that we do not know much about what the conditions of practise actually are, and there is considerable question as to whether the 45 deg. spray simulates them any better than any other method of procedure would. In any case, what is the difference provided we have certain values which we know approach the practical value of the insulator? Is it not much better to have a condition of test which we can repeat with some assurance of accuracy even though it does not simulate completely the conditions of practise?

There is nothing said about cement—how the insulator shall be handled after it is cemented. In the first place, it should not be used soon after cementing, and should be kept above the freezing point. I know of some pieces of work in which the insulators were allowed to freeze before they set and when they got out on the line there was some trouble. That was a case where it was not possible to test the insulators as a completed whole, and they had to be tested in separate parts. When you test them after assembling, that point is not of such great importance, except that it is always important not to have your deliveries held up by the failure of a lot of insulators, and, of course, that is important from the manufacturer's standpoint, not to lose a lot of the product.

I should also like very much to hear from the insulator manufacturers as to the absorption tests which have been proposed, whether or not they are satisfactory to them, whether they are too difficult, or whether they are likely to result in a product whose existence is not justified.

I would also say that I agree with Mr. Nicholson in his remarks in regard to the flash-over values of the insulators. It seems to me that a desirable insulator is one which will flash over the unit always before it will puncture. If that is the case, why not space your units far enough apart so that approximately, at least, you get the benefit of the full value of each unit? If there is a power arc-over, as a rule it will go to the outside plenty quick enough. I doubt if you will find any difference in the breaking of the insulators whether the power arc starts around the insulators or between them. If the amount of power is enough to break the end unit, it may go along a line of insulators, a string of units, if the arc persists long enough. Whether it flashes clear around the string, or starts clear around individual units, there is little difference in practise, so far as we have been able to observe.

Percy H. Thomas: President Mershon was the one who suggested having the spray vertical and the insulator at 45 deg.

Of what effect, in one of these specifications, would be the provision that we separate the design test from the routine test, as you suggest? What would you have done with the specification?

Ralph D. Mershon: I would place the most stress upon those things which will control the product as we go through the process of manufacture. I do not think I would put the matter of design in the form of a specification at all. I do not see why we should supply specifications for the design of the insulator at all. It is likely to impair progress, I think, and in any case the engineer in charge of the work ought to have enough knowledge and experience to exercise his own judgment in regard to questions of design. The usual course is to get samples from the different manufacturers and test them. If there are any new designs which have been brought out, you can compare them with regard to corona and in regard to string ratio, and all of the other points that are involved in the design of the insulator itself and in regard to the puncture value of the insulator. After you have done that, you want a specification to which you can fairly require conformity, and it will result in bringing forth as uniform a product as the state of the art will permit.

Percy H. Thomas: Is not that exactly what we have in the first specification? We have the routine test separated from the design test in a perfectly plain manner. The first part may not be called a specification, but have these things stated, and call attention to the necessity of uniformity in the product and leave the greatest freedom for variations in design. We do not limit the development of the art, but want to call attention to the way tests should be made, and things of that sort. I agree with you in the matter.

Ralph D. Mershon: The remarks I would add in regard to that would be directed more against the supplying of specifications for design at all. Any specifications we agree upon should be directed toward bringing the product through and not to the matter of the design of the product.

E. M. Hewlett: I think that the last point Mr. Mershon brought out is one of the most important. The general design of the system should be settled before any decision is made as to the particular insulator which should be used. The proper insulator to use will be determined by the voltage of the line. An insulator designed for a 70,000-volt line would naturally show corona at a lower point than an insulator designed for a 100,000-volt line. Also, insulators designed for any given voltage at a given altitude will show corona at a lower voltage at higher altitudes. Thus at points where a line crosses a mountain range it might be necessary to use insulators of a different design than those used at lower points so that all the insulators will show corona at about the same voltage.

In reference to the arc-over test, we find that many manufacturers consider a puncture or a flash-over test with a testing transformer equivalent to an actual line test, but Mr. Mershon has

shown the fallacy of this. He brought out the point that whereas you might flash over and strike between the insulators and probably break the whole string, the power arc-over, that is, the arc-over on a power system, as distinguished from a flash-over on a testing transformer, often improperly called a power arc, would probably throw clear of the insulators in an instant. If the insulators fail it may be because a w nd is blowing at the time, whereas a similar flash-over clear, without adverse wind, might not have created any trouble. The flash over the entire string of insulators might have been blown into the string of insulators if it had been drawn in by a flash in between.

In reference to the rain test, the 45-deg. angle test, the amount of water, etc., I find that many times tests are run with an abnormally large amount of water, a great deal more than actual precipitation conditions justify, the insulators being first tested under actual precipitation conditions and then, if they do not arc over, the amount of water is increased until the insulators do arc over. It would seem a much better test to duplicate actual precipitation conditions, increasing the voltage until a flash-over results, because this method gives a better idea of the behavior of the insulators under actual conditions. It should be obvious to everyone that when excess water is used, the information being sought from the test is not and cannot be obtained, which is the maximum possible arc-over voltage at maximum rain conditions and not at five times this point.

Now considering the rain test at an angle of 45 deg. If rain is falling at 45 deg. there is considerable wind, and if the wind condition is not duplicated in the test, the water will stream over one disk to another and the insulators will flash over at much less voltage than they would under actual weather conditions because of the wind blowing the streams of water so that they will not drip from one disk to the next one below it.

Then there is another point. We have seen tests where the insulators were damaged because they were too far apart, whereas the individual test on each disk was good. Because the insulators were placed a little far apart, they flashed around the individual disks, whereas if they had been placed closer together the flash would have been around the whole string. Also insulators are often arranged simply to meet the ideas of the engineers testing them, making the test a personal rather than a physical equation.

In reference to the absorption, while 0.01 of one per cent in porcelain is possible, I doubt whether this absorption can be maintained at this time in the case of large orders, because there is a difference in the temperature in different parts of the kiln, as well as in the different burnings, etc. If you demand 0.01 of one per cent absorption, I think it probable that the cost will be increased.

On the basis of cost, I think also that the tests suggested are too long, and that too many insulators are tested. The purchaser will have to pay the additional cost, it has to go

somewhere, and if the insulators are subjected to severe tests and long tests, which entail some hardship on the manufacturer, the extra expense must naturally be put into the price of the product.

The altitude is not considered in the specifications, and I do not suppose that it should be, but a reference should be made so that it will be remembered by engineers selecting insulators for higher altitudes. In this connection, if only a small portion of the line runs at a higher altitude it would be a hardship to make a specification for this altitude include all the insulators which are used at the lower altitude.

P. H. Thomas: I think you are right about that.

E. M. Hewlett: Regarding the appearance of the corona at different altitudes—an insulator of a given design and with a certain size pin will show corona at a definite altitude with given climatic conditions, and some reference should be made to this so it will be considered in selecting insulators for various altitudes. There should be a practical specification drawn up for the inspector's use, so that he can determine whether the insulators received are made of the proper material and are of the dimensions called for, etc., and that they will pass certain electrical tests. I also believe that specifications should not specify the details of manufacture, because no good would be accomplished. It is always to the interest of the manufacturer to work out efficient methods of design and manufacture to accomplish the various purposes desired and he is often not in a position to manufacture, without added expense, according to other methods which might be specified. If you limit the man in the porcelain factory in the making of porcelain or seek to influence the way in which he handles his materials, you are going to handicap him seriously, because some clay combinations are more suitable for thick bodies and some for thin bodies, and the characteristics of the clay must be considered in working out a design for a given purpose.

In reference to the porcelain, I have been working out different designs of porcelain for the last fifteen or eighteen years, and I agree with anything that anyone says about the varying character of the product. We make insulators of various kinds, as it is necessary to do so in order to obtain the different forms which are required. It is often difficult, if not impossible, for us to obtain just what we need from outside manufacturers. From experience I have found that the ceramic engineers and foremen in charge of the porcelain factories often unintentionally mislead us as to the form in which it is possible to make given insulators. There are many factors to be considered in manufacturing porcelain that do not occur in other lines, and it takes a great deal of experience with the design and manufacture of porcelain and its uses for one to be reasonably able to predict what results will be obtained from various designs.

As to the advisability of making up the strings of units which will not flash over before the line potential is reached, this may be feasible for some voltages, but it is obvious that after a certain voltage is passed it will not be practicable. For instance, it would be difficult at the present time to make up a string of insulators for a 140,000-volt transmission line in which each unit in the string could be tested to flash over at line voltage, 140,000 volts. Such a design would be practically prohibitive.

The specifications given for suspension insulators often call for strength far in excess of the strength of the conductor and the possible strains on the system, and consequently introduce a factor which may call for a design of insulator electrically inferior, though testing mechanically stronger than is necessary, whereas if the specifications did not call for these excessive strengths, better electrical characteristics could often be secured. It should be kept in mind that the initial strain which an insulator will stand does not necessarily prove that it will maintain this great strength over a long period. Some insulators that have stood great strains at first have been known to drop the conductor in a comparatively short time after having been put in service and having been subjected to only a small portion of the original testing strain, due to the methods of fastening the links together.

As to the mechanical test, I think the points made by Mr. Sandford and Mr. Nicholson about this are correct. I think they should be made as general tests, though, and only a comparatively small number would be necessary to test in that way. You ought to test your design in that way, the same as you would for other designs, and then run at a proper safety factor and use enough strain insulating sections in multiple to get the desired strength. Then as to the suspension insulator. A suspension insulator is not ordinarily called upon to stand so much strain as a strain insulator, even under emergency conditions, as the suspension insulator is nearly always put on the lighter tower, and if subjected to the same strain as the strain insulator the tower would probably be pulled over.

H. W. Crozier: I want to say a word in regard to the matter of vitrification. There are two kinds of tests, one a general test as to the material you are going to get and another a detailed test of each particular piece of porcelain. There is nothing said whatever in the specification about the vitrification test of each particular piece of porcelain. When I first learned something about the porcelain business, Mr. Sandford was working on the same problems. We would set up a long row of insulators for test and very quickly the inspector learned to pick out pieces of porcelain which were not thoroughly vitrified. Many pieces, however, were doubtful and it was found that soaking in a tub of water over night had a very great influence on the insulators. A large proportion selected by the inspector as doubtful would fail after the soaking test, showing insufficient vitrification.

As has been said here, the manufacture of insulators is not by any means uniform, and from any one kiln you can take insulators which are very fine and right alongside of them you will find insulators which are not vitrified. After a little experience, the suspected ones are picked out and set aside, and sent back to the oven and refired, and by that means the manufacturer saves the loss which would be caused by their failure. I would like to see something put in the specification to cover this question of test for the vitrification of individual pieces. I think the best way to do that is to take the porcelain and soak it in water—that would be the test which I should apply. Whether we should require this 0.01 per cent of absorption, I do not know, but soaking in water will soon determine. We can get a porcelain insulator which will stand the electrical test, but we want to be certain that the insulator will not deteriorate in service. In the same lot of insulators that I have spoken about we did have a large number of insulators deteriorate in service. That was due to the fact that the insulators were not thoroughly vitrified. They were made in a new factory and no one had sufficient experience to properly select the insulators which were not thoroughly vitrified. If these insulators had been soaked, I believe not many would have passed the test. After the line had been in service about two years, one section of the line where the first four carloads were used was found to give a great deal of trouble due to failure of insulators.

As to the other question raised about the strain insulators, in regard to the mechanical test, words have been put into my mouth which I did not use. I anticipated we would use two different types of insulators. If we are going to apply additional tests to a lot of insulators, we will naturally raise the price, so it would be better to have one lot of insulators for the strain insulators and another lot of insulators for the span insulators. If the span insulators are accidentally seriously loaded, and break in the line, that is a very serious matter, but one which should be carefully considered in the design. As a rule, for heavy loads it is better to use two or three strings of insulators in parallel for strain insulators.

P. W. Sothman: The problem before us is one that cannot be disposed of by following ordinary thumb rules. To me, every insulator represents an integral part of a system, requiring a special study for each individual installation. For it is obviously impossible to select an insulator for a certain service and then assume that this same insulator will withstand any other service under any other conditions, on the strength of the fact that the voltage of the line is the same.

I believe it would not be wise to draw up specifications for the manufacture of insulators by setting cast-iron rules for the manufacture and testing. What is most needed in these specifications is well-defined principal requirements. And, further, I believe the manufacturer and the engineer should arrive at a

mutual understanding as to how the best results can be obtained. I think one of the most advantageous things from a practical point of view which we can undertake to do is to urge the manufacturer to improve the character of the porcelain, in order to obtain a more uniform product.

Mr. Peek has advanced several points which can only be viewed from a purely academic standpoint, and Mr. Sandford has given us his views from the manufacturer's standpoint. Mr. Sandford does not wish the engineer to settle all questions, but wants to give us what he thinks best and not necessarily what we need. I think we should specify clearly what we need. But do not let us step in and tell him how to do it. It is his business to know that.

With reference to the tests of the insulators, it appears that tests on dry and wet insulators vary considerably. I do not believe that any of our practical engineers have ever seen an insulator fail under a wet test, and in spite of this they still specify wet tests. It was pointed out, and I think it was endorsed by Mr. Sandford, that the water used for these water tests has a range of 100 per cent in conductivity. Mr. Mershon remarked that some water was a good insulator and other water a good conductor, and I have always found that to be the case. I have seen wet tests on insulators that did not leave anything to be desired; however, when the insulators were tested in another room, they failed entirely, under apparently the same test.

I absolutely agree with the remarks of Mr. Lincoln, who recommends the use of water from condensed steam. I agree with him that we should approximate as closely as possible the natural conditions, in specifying our tests. There is nothing gained by overstressing the insulator to such a point that it will fail soon after it is placed on the line. We want a commercial piece of apparatus, and for this reason we will have to be less academic and more practical in calling for something which will satisfy the operator. Now, to obtain these conditions, if the gentlemen who are in charge of the practical operation of a transmission line will join hands and heads with the insulator manufacturer, and study the subject thoroughly, we would be sure to obtain better results, and for that reason I would suggest that a resolution be passed turning over the work of the gentlemen who have presented these specifications to a committee to be appointed to work out the details in coöperation with the manufacturers, in order to avoid the danger of framing a specification that would do more harm than good. It should always be borne in mind that a chain is only as strong as its weakest link. The breaking down of insulators does not necessarily imply that the insulators, themselves, are at fault. In a good many cases, the trouble has its seat elsewhere. Distribution of stresses along the string of insulators and at their extreme ends, the design of cable clamps, its protection, etc., etc., all must be duly considered. Until all troubles and their causes are clearly

understood and their relative value appreciated, both qualitatively and quantitatively, nothing can be gained by blindly adding material to an insulator with the object of making it safer against these causes.

C. F. Scott: The problem seems to be a triple one: first to determine, by research, what it is possible to secure in the way of satisfactory insulators; second, to determine, by research, what characteristics an insulator should have in order to be wholly satisfactory; and third, a commercial test to determine whether particular insulators meet these requirements, and conditions. The three elements are—research, engineering and commercial testing.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y.. June 25, 1913.

THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING

BY F. D. NEWBURY

Considerable information has been presented before the Institute and elsewhere concerning the performance of self-starting synchronous motors, but this has dealt mainly with the mathematics of initial starting torque and current and the performance under a few of the simpler conditions of starting voltage, load and excitation. There is much more than this involved in the complete starting operation, and the purpose of the present paper is to describe—from the physical point of view—what actually takes place in the motor windings under a wider range of starting conditions. The information presented in the form of oscillograms is not only interesting in its bearing on synchronous motor operation, but as experimental data illustrating principles common to alternating-current circuits in general.

Two machines have been used in the experiments described: a 200-kv-a., 2400-volt, three-phase, 600-rev. per min., standard belted generator and a 150-kv-a. generator of the same characteristics and of the same general design. These two generators have the same number of poles and rotor diameter and, in fact, use the same rotor punchings, so that the design proportions are very closely the same. Both generators are provided with a copper damper winding of the general type shown in Fig. 1. These machines, having been designed as belted generators, have only average performance characteristics as self-starting synchronous motors. The damper winding is of low resistance to serve as a damper during synchronous operation, and as a starting winding for usual synchronous-motor applications where the initial starting torque is not large.

The complete starting operation may be conveniently divided into three parts, as follows:

1. Motor starting from rest at reduced voltage and no excitation.

2. Motor running on partial voltage without excitation in synchronism; excitation then applied.

3. Motor running on partial voltage, excited, and in synchronism; voltage then increased to normal line voltage.

There are two additional variations of the third part of the starting operation which can most conveniently be classed as additional parts, as follows:

4. Motor running on partial voltage, without excitation, with external load, field not excited and motor not in synchronism; field then excited and synchronism attained and full voltage applied.

5. Motor running on partial voltage, with external load, excited, but not in synchronism; line voltage then applied and synchronism attained.

The subject will be treated under headings corresponding with these five parts of the starting operation.

I—Motor Starting from Rest at Reduced Voltage; No External Load

(a) *Field Circuit Open.* This condition is shown by Fig. 2. The motor is started by the application of approximately $\frac{1}{3}$ normal voltage with the field open-circuited and with no external load. A shunt transformer, connected across the field terminals, affords a record of the voltage by the oscillograph. It will be noticed that the maximum current of 106 amperes resulting from the application of voltage is maintained at an approximately constant value until the motor is well up to synchronous speed. The voltage induced in the field winding, as is well known, is a maximum at start and has a frequency equal to that of the supply circuit, the frequency gradually decreasing until it becomes zero when the motor is in synchronism. The voltage is proportional to the rotor frequency, or slip.

(b) *Field Circuit Closed.* The conditions shown by Fig. 2 are duplicated in the oscillogram Fig. 3, except that the field is closed through its rheostat, the combined resistance of the rheostat and field winding being approximately 8.5 ohms. The armature current is slightly increased, having a value of 120 amperes instead of 106 amperes. A current of 10 amperes (maximum

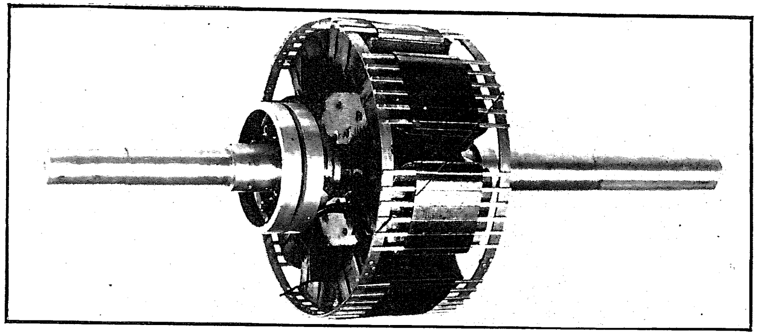
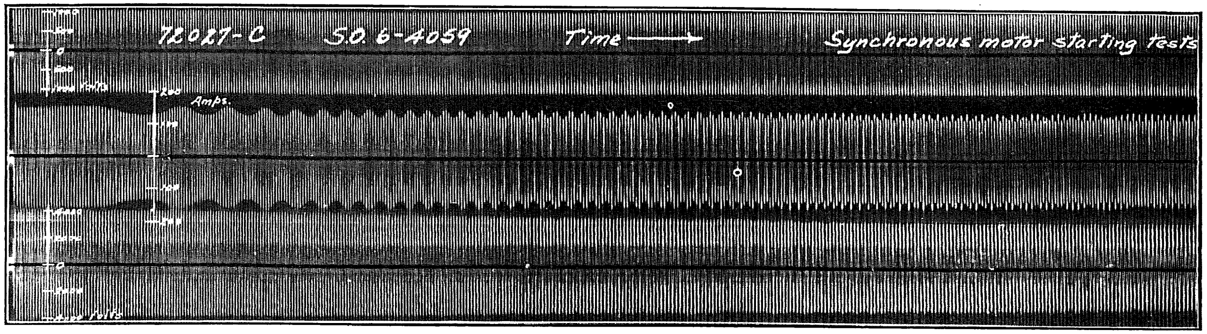


FIG. 1—TYPE OF DAMPER CONSTRUCTION [NEWBURY]



[NEWBURY]

FIG. 2—OSCILLOGRAM SHOWING STARTING CONDITIONS WITH $\frac{1}{3}$ VOLTAGE, NO EXTERNAL LOAD, *Open* FIELD CIRCUIT, 150-KV-A. MOTOR

Upper record motor voltage. Middle record armature current in one phase. Lower record field *voltage*.

PLATE XXIV
A. I. E. E.
VOL. XXXII, 1913

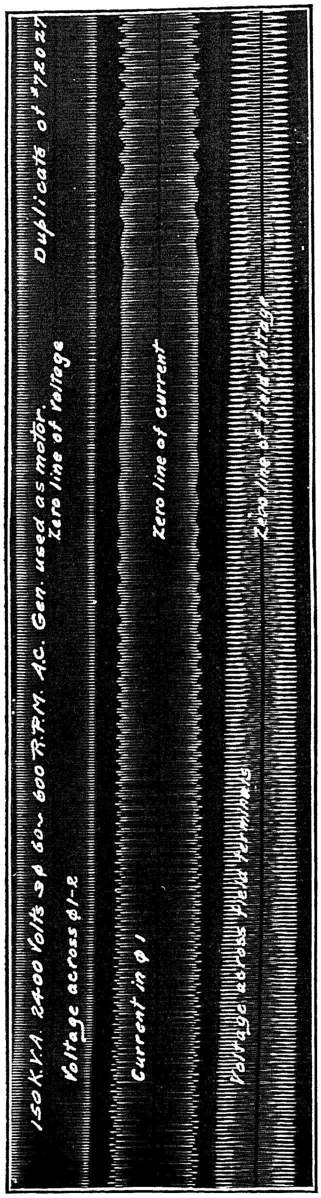


FIG. 2—(*Continued*)

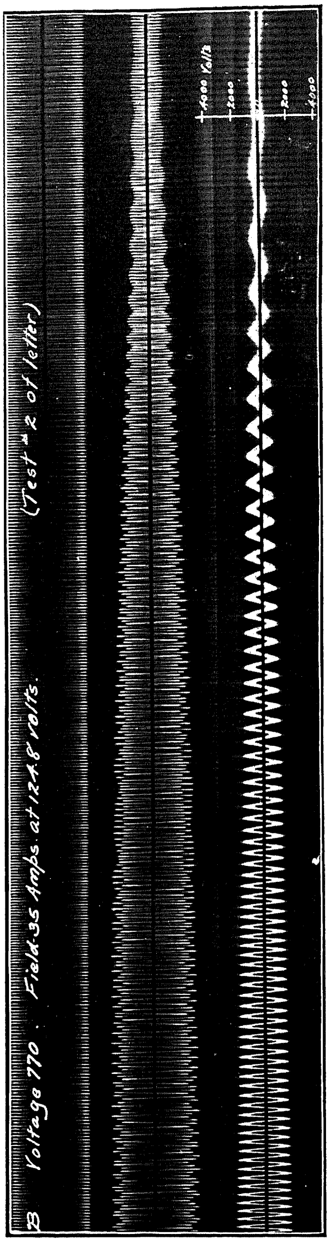
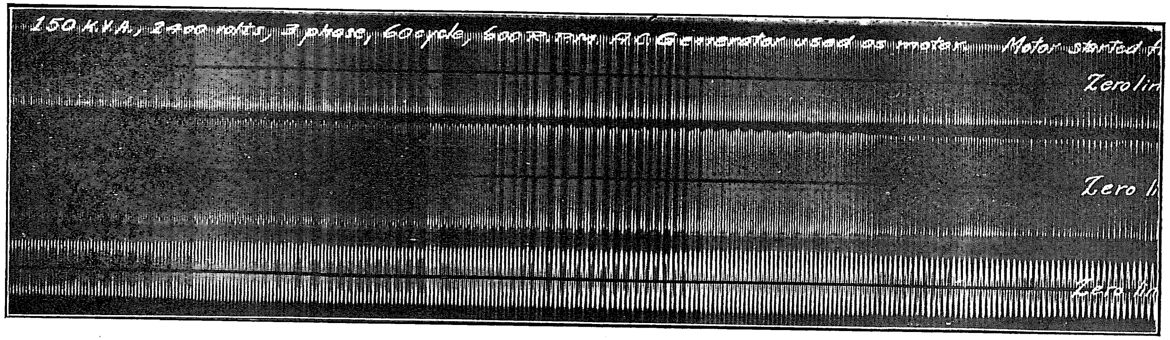


FIG. 2—(*Continued*)

PLATE XXV
A. I. E. E.
VOL. XXXII, 1913



[NEWBURY]

FIG. 3—OSCILLOGRAM SHOWING STARTING CONDITIONS SAME AS FIG. 2 EXCEPT *Closed* FIELD CIRCUIT, 150-KV-A. GENERATOR

Upper record motor voltage. Middle record armature current. Lower record field *current.* Printed oscillogram does not show first few seconds of starting.

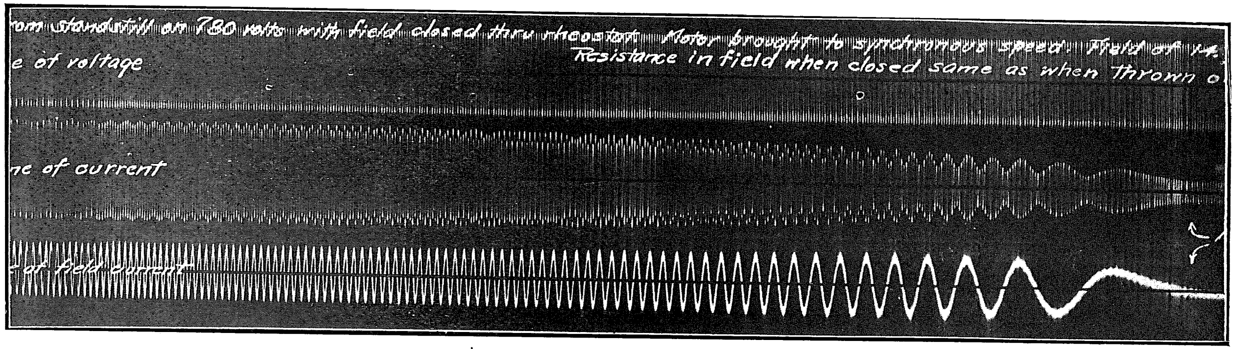
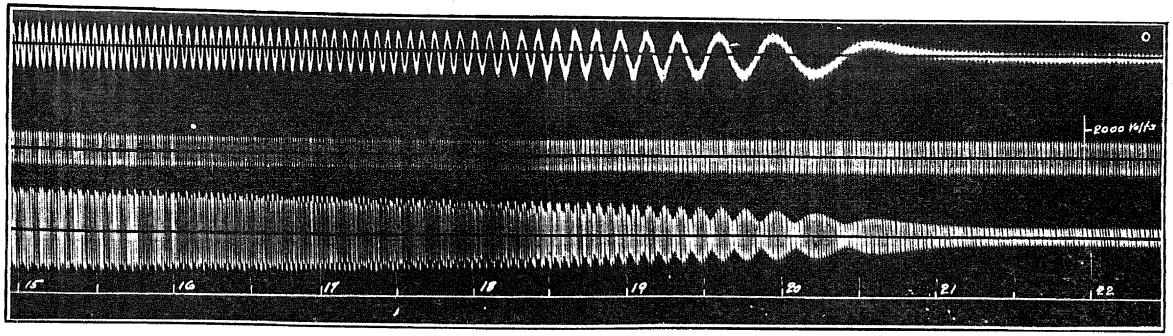


FIG. 3—(*Continued*)



[NEWBURY]

FIG. 4—OSCILLOGRAM SHOWING STARTING CONDITIONS WITH $\frac{1}{3}$ VOLTAGE, NO EXTERNAL LOAD, CLOSED FIELD CIRCUIT, 200-KV-A. MOTOR

Upper record field current. Middle record motor voltage. Lower record armature current. Printed oscillogram does not show first 15 seconds of starting.

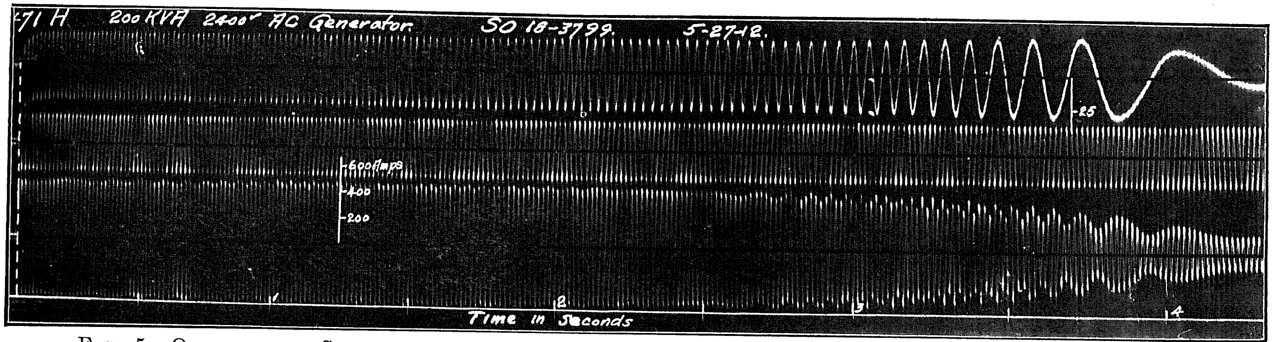


FIG. 5—OSCILLOGRAM SHOWING SAME STARTING CONDITIONS AS FIG. 4 EXCEPT $\frac{2}{3}$ STARTING VOLTAGE [NEWBURY]

Motor reached synchronism in $5\frac{1}{2}$ seconds as compared with 21 seconds in Fig. 4. Upper record field current. Middle record motor voltage. Lower record armature current.

value) is induced in the field winding and is maintained at this value until the motor is within a few per cent of synchronous speed. This field current is alternating, and, like the field voltage in Fig. 2, has a frequency equal to the slip. There is a pulsation in the armature current corresponding to the frequency of the current in the field circuit, these pulsations becoming very pronounced near synchronism. Although the value of the voltage induced in the field circuit is proportional to the slip, as shown in Fig. 2, the current is practically constant, due to the

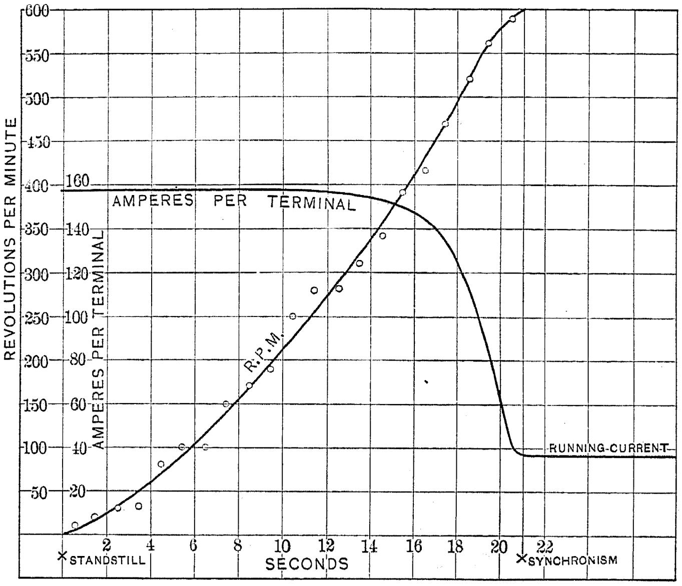


FIG. 6—SPEED AND CURRENT DURING STARTING UNDER CONDITIONS OF FIG. 4

reactance of the field winding and the voltage decreasing at the same rate. The constant resistance of the field circuit has a negligible effect until the reactance has become practically zero near synchronism. This illustrates very clearly the reason why resistance connected in the closed field circuit has practically no effect on the armature current and torque until the resistance has been made at least equal to the reactance at normal frequency. Figs. 2 and 3 show results from the 150-kv-a. motor. Similar results from the 200-kv-a. motor with closed field circuit are shown in Fig. 4, with $\frac{1}{3}$ normal voltage, and Fig. 5, for $\frac{2}{3}$ normal

voltage. The fact that the frequency of the current induced in the field winding is equal to the slip makes it possible to plot a curve showing the relation between speed and time. Such a curve plotted from the oscillogram in Fig. 4 is shown in Fig. 6 for $\frac{1}{3}$ voltage, and from the oscillogram in Fig. 5 is shown in Fig. 7 for $\frac{2}{3}$ voltage. To these curves have been added the current curves which illustrate the point already made, that the maximum current is maintained at a constant value until synchronism is nearly reached.

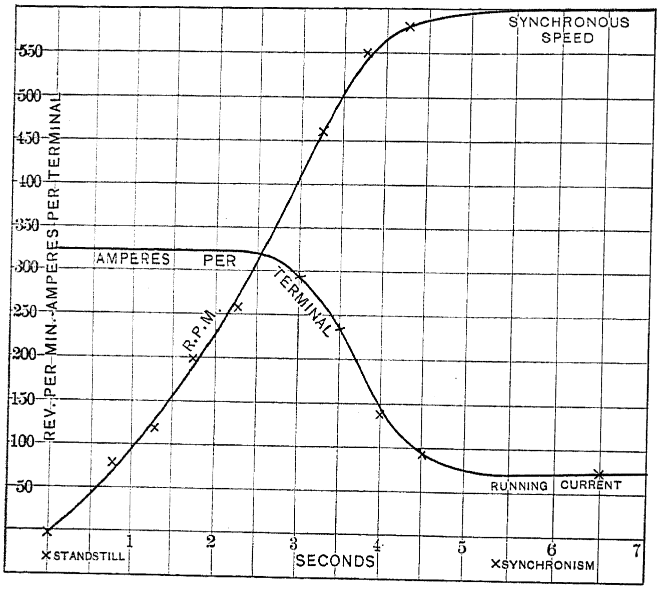


Fig. 7—Speed and Current during Starting under Conditions of Fig. 5

The effect of the closed or open field circuit on the torque developed is shown in Figs. 8 and 9 for the 150-kv-a. motor. Fig. 8 shows the current and kilowatts existing when varying voltage is applied to the armature, the rotor being locked. Under these conditions, the observed kilowatt minus the armature loss represents the loss in the rotor, and this in turn is proportional to the torque developed at the instant of starting. With the field circuit closed, the loss due to the single-phase current in the field winding is not effective in producing torque, so that the two curves are not exactly comparable. The loss in the field winding,

however, is negligible, so that this fact does not appreciably affect the statement made. It will be noted that the rotor loss is slightly greater with the field short-circuited than with the field open-circuited, showing that the short-circuited field, at least, has not been a serious detriment to the development of torque.

In Fig. 9, the starting torque is shown directly as measured by brake-beam and scales for a 150-kv-a. motor of the same design, except with a different armature winding for 440 volts.

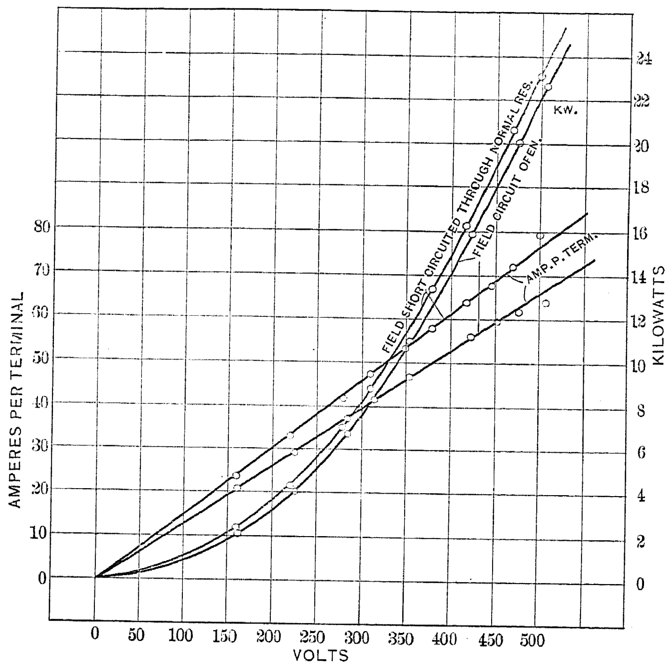


FIG. 8—COMPARATIVE STARTING TORQUE WITH CLOSED AND OPEN FIELD CIRCUIT—150-KV-A. MOTOR—COPPER DAMPER WINDING

The armature turns, however, in the two motors are proportional to the voltages. Torque curves are shown with the field circuit closed and with the same damper winding as used in the motor used in the oscillograph tests, and with a damper winding composed of brass bars instead of copper bars. With the latter damper winding, the curves show a material increase in torque with the field open as compared with the field closed.

Figs. 8 and 9 illustrate a condition generally true: that with an effective low-resistance damper winding, the torque and armature

current are very little affected by the closed field circuit, but that with a high-resistance damper winding, or with a rotor construction that permits only an ineffective damper winding to be used, the closed field circuit has a marked effect in reducing the initial starting torque. The field winding may be considered as an additional winding in parallel with the squirrel cage winding. Whether it has an appreciable effect in decreasing the torque for

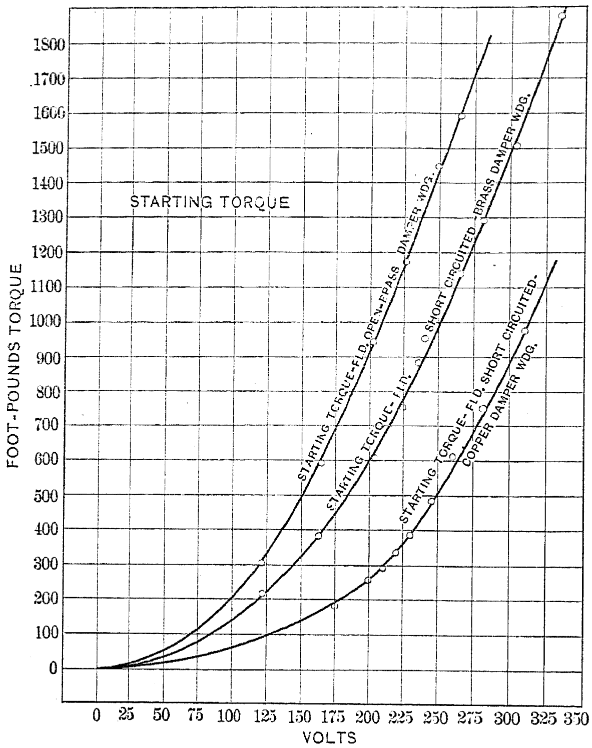


FIG. 9—COMPARATIVE STARTING TORQUE WITH CLOSED AND OPEN FIELD CIRCUIT, HIGH AND LOW RESISTANCE DAMPER WINDINGS

a given voltage depends simply on its resistance compared with that of the squirrel cage winding and the relative currents in the two windings. It is of interest to note that with a combination of field and damper windings such that the closed field winding has an appreciable effect on the torque developed, there is a considerable tendency for the motor to lock at half speed, the effect being the same as a phase-wound induction motor with one phase open-circuited.

It will be noted in Fig. 2 that the induced voltage has a value of approximately 4000 volts maximum, or 2800 volts, effective value. With a higher exciting voltage, requiring more turns in the field winding, or with a higher resistance damper winding, this voltage would have been considerably higher. For self-starting synchronous motors started with the field circuit open, the present standard insulation test of 5000 volts may be exceeded in many cases by the actual voltage obtained in operation, and in few cases does it give the same factor of safety that is given by the standard tests for the armature winding.

These facts show the desirability of starting synchronous motors with the field circuit closed (and so eliminating the high voltage from the field winding and switchboard), except in special cases where unusually high initial starting torque is required. For such applications a high resistance damper winding is necessary, the benefits of which in producing torque would be largely nullified by the closed field circuit. In such special applications, however, care must be taken to insure that the insulation of the entire field circuit will withstand the resulting voltage.

II—Motor Running on Partial Voltage with Closed or Open Field Circuit with No External Load and in Synchronism; Field then Excited

With the motor running with zero field current in synchronism, the effect of the application of exciting current is shown in Figs. 10, 11, 12 and 13. Fig. 10 and Fig. 11 show results with the 200-kv-a. motor and are continuations of the same oscillograms shown in Figs. 4 and 5. These oscillograms show a gradual increase in field current and a preliminary decrease followed by a steady increase in the armature current. Fig. 12 duplicates exactly the conditions of Fig. 10 but the results are markedly different. The armature current immediately starts to increase instead of first decreasing as in Fig. 10, and reaches its final value only after successive pulsations lasting 8 or 9 seconds. The field current, instead of steadily increasing to its final value as in Fig. 10, pulsates synchronously with the armature current. When steady conditions are attained, however, the values in Figs. 10 and 12 are substantially the same. Fig. 13 shows a similar result with the 150-kv-a. motor.

An examination of a large number of oscillograms taken shows no fixed relation between the occurrence of the steady increase in field current and armature current as in Fig. 10 or the pulsating

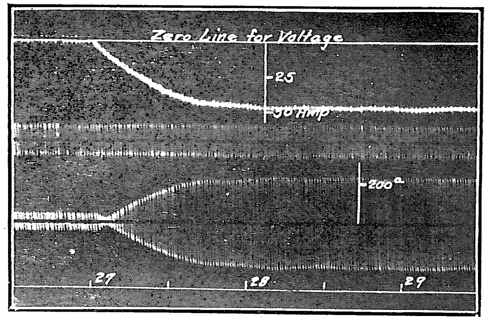
increase as in Figs. 12 and 13, and other conditions of operation. The most reasonable assumption is that the steady increase occurs when the field current and armature current at the instant of closing the field switch agree in polarity, and that the pulsating condition occurs when they do not so agree. The immediate increase in armature current in Fig. 12 when exciting current is applied is, under this assumption, required to maintain the necessary net excitation required for the applied voltage and flux. The succeeding decrease in armature current is caused by the rotor " slipping a pole " to bring the armature and field excitations in phase. The relative change in armature and field polarity requires a decrease in field excitation to maintain constant, flux, as shown by the oscillogram. If, when the rotor " slipped a pole," it remained in synchronism with the armature, the armature and field currents would gradually increase to their final steady value, as in Fig. 10. The succession of pulsations shows that the rotor oscillates back and forth, succeeding oscillations decreasing in amplitude until the rotor settles into its final relative position.

In all of the oscillograms so far shown, the excitation has been much more than that required to maintain minimum armature current with 100 per cent power factor, so that the final steady value of armature current has been greater than that required with zero rotor excitation.

III—Motor Running on Partial Voltage, Excited and in Synchronism, With and Without External Load; Line Voltage then Increased to Normal

This condition is shown by Figs. 15, 16 and 17, representing an initial voltage $\frac{1}{3}$ of normal and no external load on the motor; Figs. 18, 19 and 20 representing an initial voltage of $\frac{2}{3}$ normal and no external load on the motor; and Figs. 21 and 22 representing an initial voltage $\frac{2}{3}$ of normal and with approximately $\frac{1}{3}$ full load on the motor.

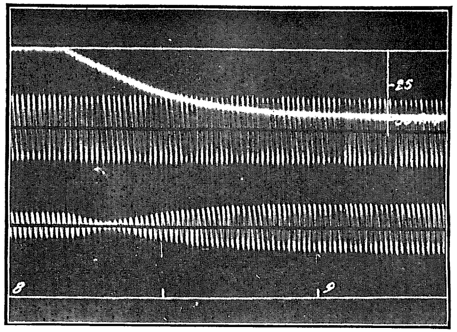
The change from the initial starting voltage to normal voltage is made by a double-throw switch. The armature circuit is momentarily opened in throwing from the low voltage to the high voltage and current drops to zero during this interval. The voltage, instead of also dropping to zero, as might be expected, increases or decreases, depending on the value of the field current. During this same interval the field current shows a marked decrease in some cases and an increase in other cases due to change in armature current.



[NEWBURY]

FIG. 10 — APPLICATION OF EXCITING CURRENT. CONTINUATION OF OSCILLOGRAM FIG. 4. $\frac{1}{3}$ VOLTAGE, 200-KV-A. MOTOR

Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature current.



[NEWBURY]

FIG. 11—APPLICATION OF EXCITING CURRENT. CONTINUATION OF OSCILLOGRAM FIG. 5. $\frac{2}{3}$ VOLTAGE, 200-KV-A. MOTOR

Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature amperes.

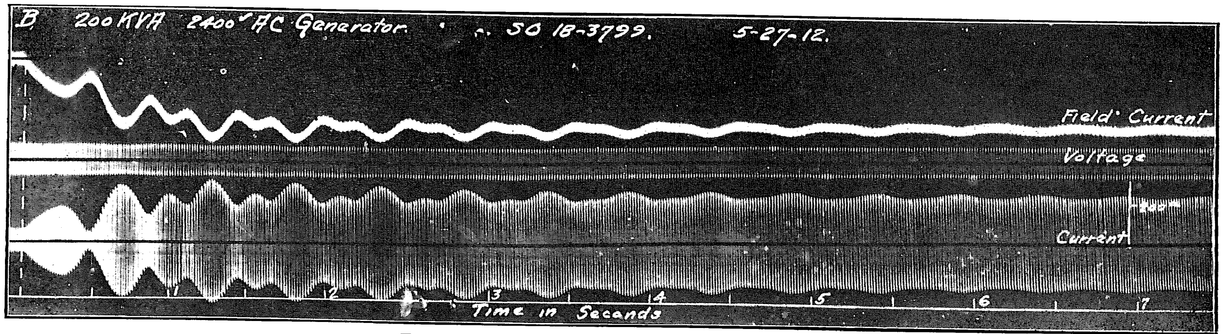


FIG. 12—APPLICATION OF EXCITATION [NEWBURY]

Same conditions as Fig. 10—pulsating current increase instead of steady current increase. Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature current.

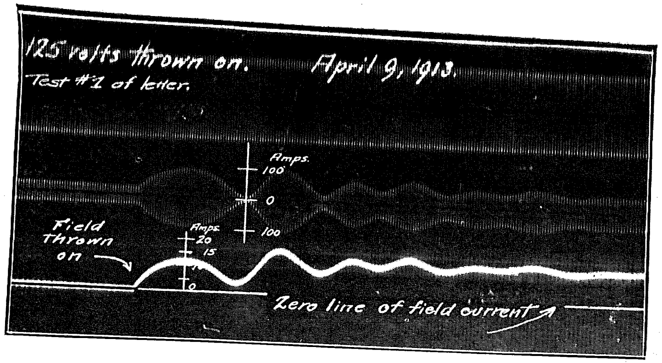


FIG. 13—APPLICATION OF EXCITATION. CONTINUATION OF OSCILLOGRAM FIG. 3. $\frac{1}{3}$ VOLTAGE, 150-KV-A. MOTOR. PULSATING CURRENT INCREASE [NEWBURY]

Upper record motor voltage. Middle record armature dampers. Lower record—field amperes—positive values above the zero line.

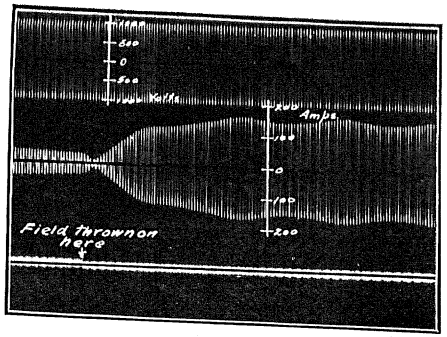


FIG 14—APPLICATION OF EXCITATION. CONTINUATION OF OSCILLOGRAM FIG. 2 [NEWBURY

Same conditions as Fig. 13 except field open circuited. For this reason there is no record of field current when field is excited.

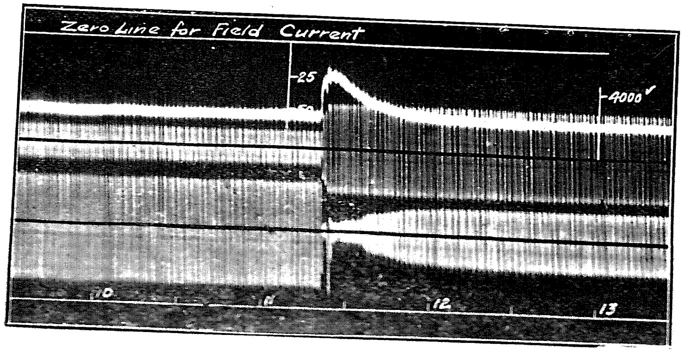


FIG. 15—APPLICATION OF LINE VOLTAGE—CONTINUATION OF OSCILLOGRAM FIG. 2. $\frac{1}{2}$ STARTING VOLTAGE 47.5 AMPERES FIELD CURRENT. NO EXTERNAL LOAD. 200-KV-A. MOTOR [NEWBURY]

Upper record—field current—positive values below zero line at top of record. Middle record motor voltage. Lower record armature current.

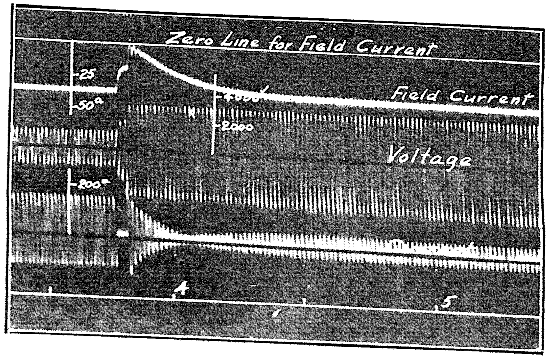
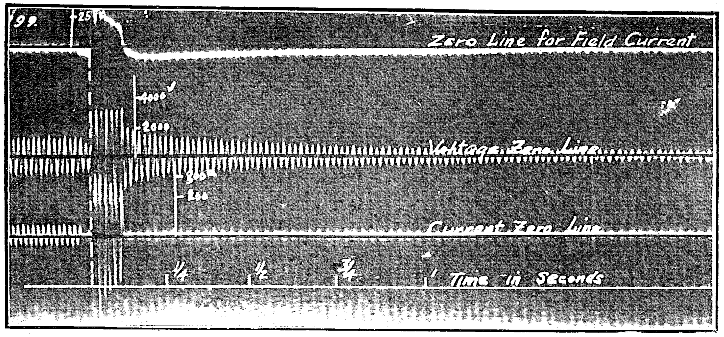


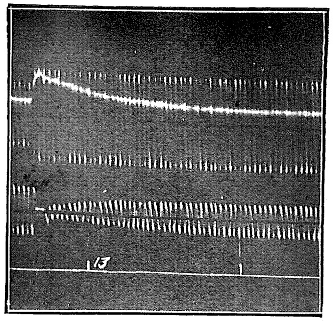
FIG. 16—APPLICATION OF LINE VOLTAGE. $\frac{1}{3}$ STARTING VOLTAGE 32.5 AMPERES FIELD CURRENT. NO EXTERNAL LOAD—200-KV-A. MOTOR [NEWBURY]



[NEWBURY]

FIG. 17—APPLICATION OF LINE VOLTAGE. $\frac{1}{3}$ STARTING VOLTAGE, ZERO EXCITATION—CLOSED FIELD CIRCUIT—NO EXTERNAL LOAD—200-KV-A. MOTOR

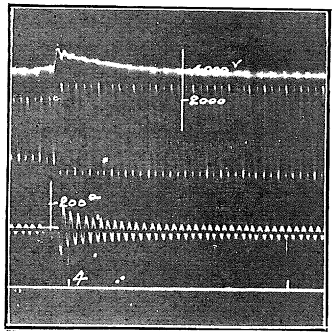
Sudden reduction of current to zero is due to accidental opening of circuit breaker.



[NEWBURY]

FIG. 18—APPLICATION OF LINE VOLTAGE, $\frac{2}{3}$ STARTING VOLTAGE, 47.5 AMPERES FIELD CURRENT—NO EXTERNAL LOAD—200 KV-A. MOTOR

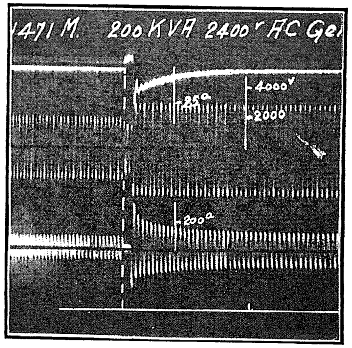
Upper record (superimposed on middle record) field current—positive values below zero line (not shown on printed section of oscillogram). Reduction in field current when line switch is closed is approximately 26 amperes. Middle record motor voltage. Lower record armature current.



[NEWBURY]

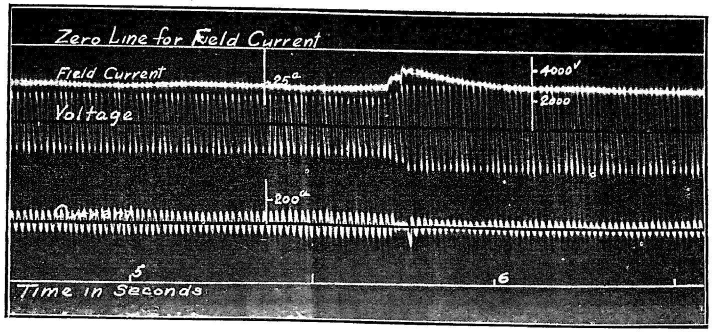
FIG. 19—APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE, 26.5 AMPERES FIELD CURRENT—NO EXTERNAL LOAD—200-KV-A. MOTOR

Upper record—field current—positive values zero line (not shown on printed section of oscillogram). Minimum value of field current when line switch is closed is four amperes. Middle record motor voltage. Lower record armature current.



[NEWBURY]

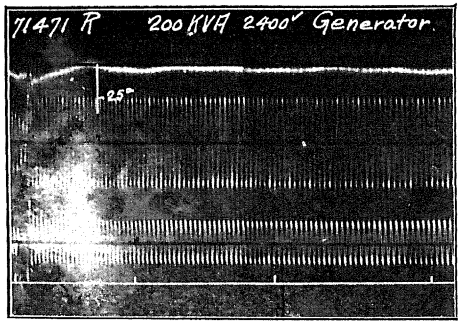
FIG. 20—APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE, ZERO FIELD AMPERES—CLOSED FIELD CIRCUIT—NO EXTERNAL LOAD—200-KV-A MOTOR



[NEWBURY]

FIG. 21—APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE—27.8 AMPERES FIELD CURRENT. 70 KW. LOAD ON 200-KV-A. MOTOR

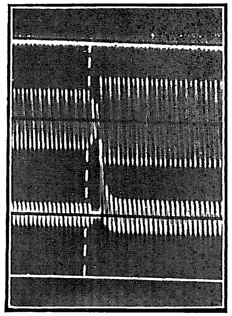
Compare with Fig. 19—same conditions except load.



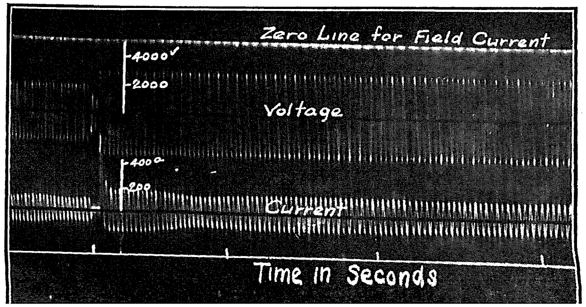
[NEWBURY]

FIG. 22—APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE; ZERO FIELD AMPERES, CLOSED FIELD CIRCUIT. 70 KW. LOAD ON 200-KV-A. MOTOR

Compare with Fig. 20. Same conditions except load. Upper record—field amperes—positive values zero line—wavy field current line indicates that motor is hunting slightly. Middle record motor voltage. Lower record armature amperes.



[NEWBURY]



The oscillograms taken do not show zero voltage during the interval the line switch is open because the counter e.m.f. of the motor is recorded. Since, during this interval, the motor is not connected to the supply circuit, the counter e.m.f. will follow the field excitation alone rather than the combined magnetizing effect of the field and armature currents; thus in the oscillograms representing excess field excitation the counter e.m.f. of the motor will increase (see Fig. 15, 18 and 21), and in oscillograms representing the under-excited condition the counter e.m.f. of the motor will decrease (see Figs. 17, 20 and 22).

When the switch is closed, applying the higher voltage to the motor, there is a momentary rush of current which may either decrease to a minimum value and then gradually increase to the steady value, or may gradually decrease to the steady value. At the instant of application of the higher voltage, the field current decreases and then steadily increases to its original direct-current value.

The reason for these relative changes in voltage and current will be clear when it is remembered that the field winding constitutes a closed circuit in inductive relation with the armature circuit, and currents will flow in this circuit in a direction to oppose any change in the flux through the circuit. Thus when the armature voltage is changed, requiring a proportional change in flux, the induced current in the field circuit will decrease the existing current if the flux is increased, and will increase the existing current if the flux is decreased. This is true whether the existing field current is more or less than required for unity power factor. The relative changes in field and armature current when the switch is opened may be similarly explained. If the motor is over-excited, as in Figs. 15 and 18, the existing armature current has a large demagnetizing component. When this is removed by opening the switch, the flux tends to increase so that the current in the field winding decreases. On the other hand, if the motor is under-excited, the out-of-phase component of the armature current is magnetizing and when this is interrupted the flux is decreased and the field current is increased.

In the operation of synchronous motors, it has been noticed that the current rush in changing from the starting voltage to the running voltage, the motor being in synchronism on the low voltage, is much larger with small field excitation than with large field excitation. In some cases the current taken by the motor with small field excitation has been sufficient to open the circuit

Fig. 26—Application of Line Voltage with Open Field Circuit. $\frac{2}{3}$ Starting Voltage. 70 k.w. Load on 200-kv-a. Motor

Compare with Fig. 22—same conditions except open field circuit.

Fig. 25—Application of Line Voltage With Open Field Circuit. $\frac{2}{3}$ Starting Voltage—no External Load—200-kv-a. Motor

Compare with Fig. 20. Same conditions except open field circuit. Upper record field amperes. (Zero because of open field circuit). Middle record motor voltage. Lower record armature amperes.

breakers or damage the starting equipment. Various theories have been advanced for this observed fact, most of them involving the different phase relations existing with different excitations. The series of tests under discussion, however, show that this factor has little, if any, effect on the current taken by the motor under the operating conditions imposed, and that the real explanation is very simple. It will be noticed in Figs. 15, 18 and 21, showing the action with maximum field excitation, that the counter e.m.f. of the motor during the interval that the switch is open, increases to meet the higher voltage applied when the switch is closed. In Figs. 17, 20 and 22, illustrating the action with zero excitation, the opposite effect on the counter e.m.f. is observed, the counter e.m.f. falling as soon as the switch is opened. Due to this behavior of the counter e.m.f., there exists only a small difference between the counter e.m.f. of the motor and the high line voltage at the instant the switch is closed when the motor is over-excited, and there exists a large difference when the motor is over-excited. To check this point quantitatively, the maximum voltage difference at the instant of closing the switch and the maximum current rush were measured on about 20 oscillograms and the results plotted in Fig. 23. This curve shows an approximate proportional relation between the increase in current and increase in voltage, irrespective of the difference between applied starting voltage and applied normal line voltage, and irrespective of the load on the motor, up to the value of load used in the tests.

Whenever the phase relation between current and voltage is changed, as, for example, when the voltage is changed with constant excitation, there is a corresponding change in space relation between the rotor and the magnetic field established by the stator, which requires a change in torque and current to accomplish it. The fact that the load upon the motor does not affect the current rush shows that this factor does not have a controlling effect on the current taken by the motor. Again, the rotor will slow down during the interval the armature circuit is open, which may increase or diminish the required change in rotor position. This also has had very little, if any, effect on the current in the tests made, but the interval between opening and closing the switch is very short, less than two cycles, and with a longer interval this factor might easily become the controlling one. Later on, oscillograms will be shown (Figs. 27 to 30) illustrating the action with larger loads, and the effect of phase position will be found to be of controlling importance.

The relation between the maximum armature current at the instant of change in voltage and the field excitation is shown in Fig. 24 for two starting voltages and with no external load on the motor. These curves have been drawn in such form that they represent the familiar *V* curves of synchronous motors with the addition of the maximum instantaneous current curves. This maximum current curve shows graphically the large increase in maximum current with small field excitation. From these curves the armature currents for the various stages of the starting operation can be obtained for any value of field excitation;

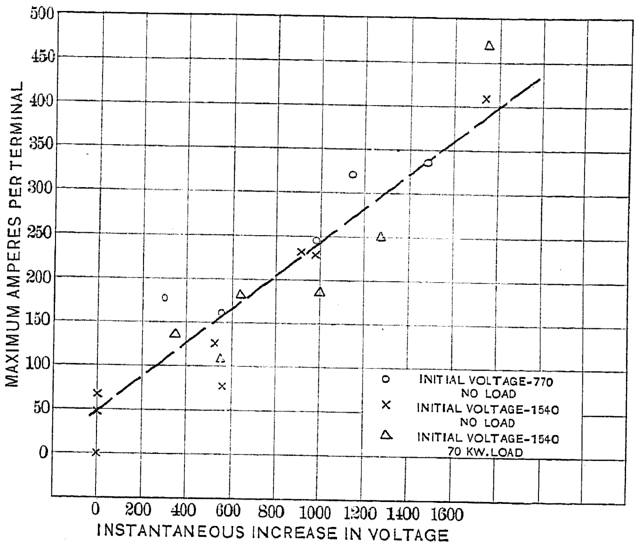


FIG. 23—RELATION BETWEEN INSTANTANEOUS CHANGE IN VOLTAGE AND CURRENT FOR THREE STARTING CONDITIONS. 200-KV-A. MOTOR

for example, with 40 amperes field excitation the motor will take a steady current of 125 amperes (curve *A*) on $\frac{1}{3}$ starting voltage. In throwing over to normal voltage, the maximum current will be 162 amperes (curve *B*) and will settle to a steady value of 57 amperes (curve *C*). Similarly, when starting on $\frac{2}{3}$ voltage instead of $\frac{1}{3}$, and with the same excitation, the motor will take a steady current of 95 amperes (curve *D*) which will decrease to the value of 46 amperes (curve *E*) when thrown on full voltage and will then increase slightly to 57 amperes (curve *C*) as the steady running value. The initial starting currents (not shown in Fig. 24) are 159 amperes at $\frac{1}{3}$ voltage and 328 amperes

at $\frac{2}{3}$ voltage. Fig. 24 illustrates the major importance of field excitation in reducing the maximum instantaneous armature current when the voltage is changed from the low to a high value. As a matter of fact, the field excitation may have a greater effect on the maximum armature current than the difference between starting and running voltages. It is usually considered of ad-

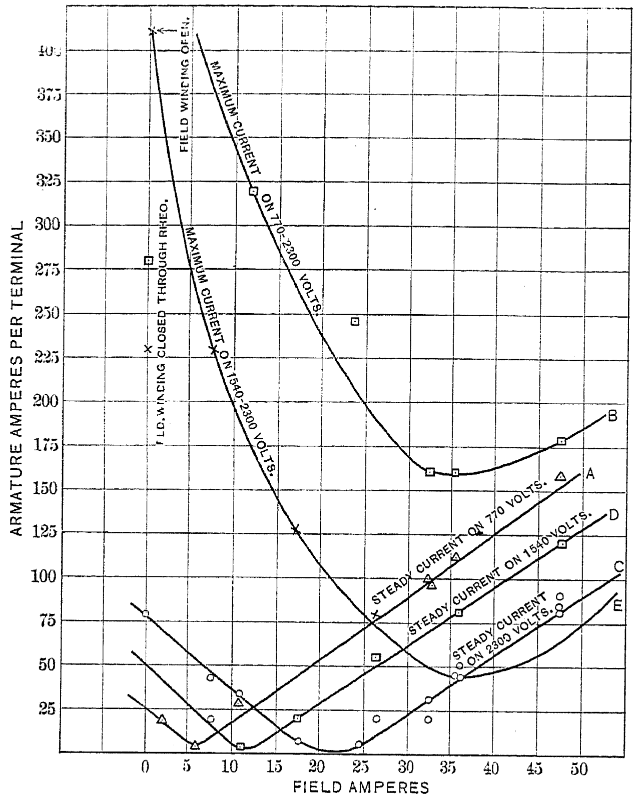


FIG. 24—RELATION BETWEEN ARMATURE CURRENTS AND FIELD CURRENTS— NO EXTERNAL LOAD—200-KV-A. MOTOR

vantage, in reducing the maximum current, to use two starting voltages instead of one; that is, starting on $\frac{1}{3}$ voltage, changing to $\frac{2}{3}$ voltage and then applying full voltage instead of applying full voltage immediately after starting on $\frac{1}{3}$ voltage. Fig. 24 shows, however, that with two starting voltages and low excitation the current rush may be greater than with one starting

voltage and high excitation. At 1540 volts and 10 *amperes*, field excitation, the steady current is 6 amperes, which increases to 200 amperes when 2300 volts are applied. On the other hand, at 770 volts and 35 *amperes* field excitation, the steady current is 106 amperes which increases to 160 amperes when 2300 volts are applied.

For the complete starting operation, the minimum starting current is obtained by starting on $\frac{1}{3}$ voltage and throwing over to full voltage after synchronism has been attained and maximum excitation has been applied. Under these circumstances, the maximum current at standstill is approximately equal to the maximum current at the application of full voltage. If $\frac{2}{3}$ voltage is initially applied, the current at the application of full voltage is materially reduced, but this is of no operating importance as the initial current is considerably increased. Also, the use of an intermediate starting voltage such as $\frac{2}{3}$ voltage between $\frac{1}{3}$ and full voltage does not result in any advantage, as in changing from $\frac{1}{3}$ to full voltage the maximum current measured by oscillograph is practically the same as at the application of the initial starting voltage. Measured by ammeter, the current at change in voltage is much less than at start.

In discussing maximum starting currents, a distinction must be made between currents measured by indicating instruments and currents measured by oscillograph. At the start the currents measured by these two methods are practically equal since the starting current is maintained at its maximum value for a number of seconds. At change in voltage, however, the current measured by ammeter very often bears no relation to the actual current measured by oscillogram since the maximum current may exist for only a few alterations.

There is one more point of interest in connection with maximum current at change in voltage which may be mentioned. Fig. 20 shows the condition with zero excitation and closed field circuit. Fig. 25 shows exactly the same conditions except that the field circuit is open. Similarly, Fig. 22 shows the same conditions as Fig. 20 except that the motor is carrying an external load. Fig. 26 shows the same conditions as Fig. 22, except that the field is open-circuited instead of short-circuited. A comparison of these oscillograms shows a marked increase in current rush with open field circuit. This is satisfactorily explained by the restraining effect of the induced field current, in the case of the closed field circuit, on any change in flux.

IV—Motor Running on Partial Load with Field Short-Circuited with External Load but not in Synchronism; Field then Excited and Synchronism Attained; Full Voltage then Applied

In the cases previously considered, the motor is in synchronism on the initial starting voltage and without excitation. Under these conditions the maximum load the 200-kv-a. motor would carry is 70 kw. Obviously, larger loads can be pulled into synchronism by exciting the motor before synchronism is attained and depending upon the excitation to pull the motor into synchronism. Unfortunately, tests under these conditions could not be made with the same motor that was used for the previous oscillograph tests. The two motors, however, are of such similar design that the loads carried, considered as a percentage of the motor normal rating, may be fairly compared. The 70 kw. carried by the 200-kv-a. motor without excitation represents 35 per cent of the normal rated torque of the motor. The 150-kv-a. motor synchronized a load of 90 kw., or 60 per cent of its normal rating with maximum excitation. The load was obtained by belting a direct current generator to the synchronous motor and loading the generator on resistance. The load varies approximately with the square of the speed (with constant resistance), the loads referred to being the maximum load at synchronous speed. This condition is illustrated in Fig. 27. The oscillogram clearly shows how the phase position of the rotor with respect to the armature current and flux is changed by the application of field excitation. During the interval that the line switch is open, the motor evidently falls behind with respect to the phase of the line voltage to such an extent that on closing the switch the motor is not in synchronism with consequent abnormal increase in armature current and variation in field current. Under this condition of load, therefore, the same simple relation between instantaneous increase in applied voltage and resulting current, as shown in Fig. 23, does not hold. In Fig. 27, with practically zero instantaneous increase in voltage the maximum current is approximately 200 amperes. In Fig. 29, with 1800 volts increase, the maximum current is only 150 amperes.

V—Motor Running on Partial Voltage with External Load Excited but not in Synchronism; Full Voltage then Applied and Synchronism Attained

Still larger loads can be synchronized if the final voltage is depended on to pull the motor into synchronism. It was found

by experiment that a load of 139 kw. could be synchronized in this manner. This load is equal to 92 per cent of the motor rating. On successive trials, loads of 139 kw., 133 kw. and 123 kw. were synchronized. Further increase in the load was limited by the assumed heating limit of the motor windings. The tested loads, therefore, do not represent the maximum loads that can be synchronized without regard to other limits. These results were obtained with a field current of 15 amperes which is somewhat less than the current required for normal voltage on open circuit. Oscillograms illustrating this condition are shown in Figs. 28 and 29. All conditions in the two oscillograms are the same except the loads carried by the motor. In Fig. 28, the load is 112 kw., and in Fig. 29, 139 kw. In both oscillograms it will be noticed that during the time the motor is excited on low voltage, and is not in synchronism, the maximum armature current on each successive swing is slightly greater. This indicates that the condition is unstable and if continued long enough the motor will swing far enough from its proper phase position to lose its torque and stop.

In Fig. 30 is shown an oscillogram for the same conditions except that the excitation is increased to 35 amperes, the field current resulting from 125 volts on the field without the rheostat. The load at synchronous speed is 110 kw. Comparing Fig. 30 with Figs. 28 and 29, it will be noted that the increased excitation is detrimental. The armature current when the field is excited is much larger and the current increases more on successive swings. The armature current and field current are greatly increased on increase in voltage to normal, and it requires a longer time (six complete oscillations instead of three) for the rotor to drop into exact synchronism.

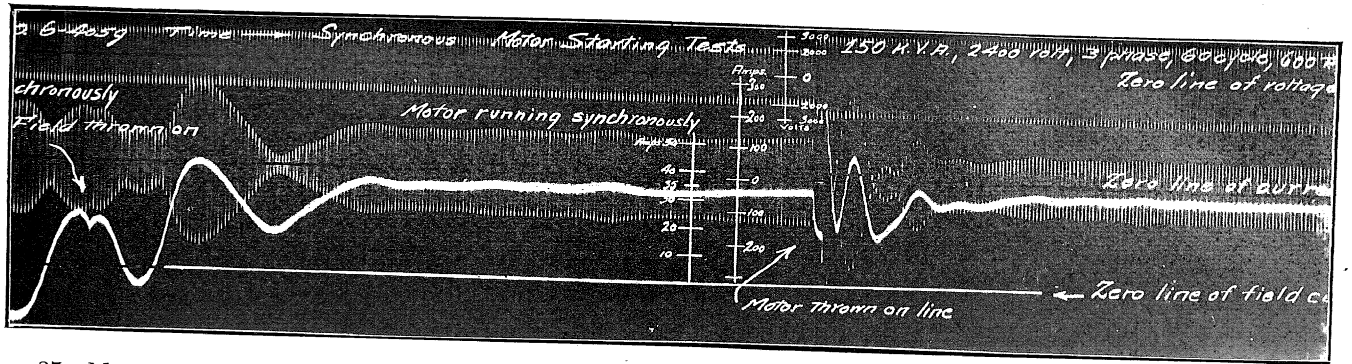
The probable reason for the better performance with under-excitation is the more advantageous initial position of the rotor (with respect to the line voltage). With under-excitation the rotor is ahead of the field due to the line voltage and with over-excitation the rotor is behind. Consequently, when the line voltage is removed and the rotor drops back due to the braking action of the load, it is not so far out of phase with under-excitation as with over-excitation. This explanation can only apply when the rotor is in synchronism on the low voltage as in Fig. 27. When the motor is not in synchronism on the low voltage, the phase position at the instant of change in voltage is not determined by the excitation, but by chance.

The complete statement of the effect of excitation on armature current when line voltage is applied, therefore, becomes:

With motor loads such that the motor is in synchronism before the application of line voltage and does not greatly fall back during the interval the line switch is open, the maximum current is proportional to the instantaneous increase in voltage and over-excitation is the most favorable condition. When, however, the motor is heavily loaded so that the motor is not in synchronism before the application of line voltage *or* does greatly fall back during the interval the line switch is open, the maximum current depends on the extent to which the rotor is out of phase at the instant of line voltage application, and under-excitation is generally the most favorable condition.

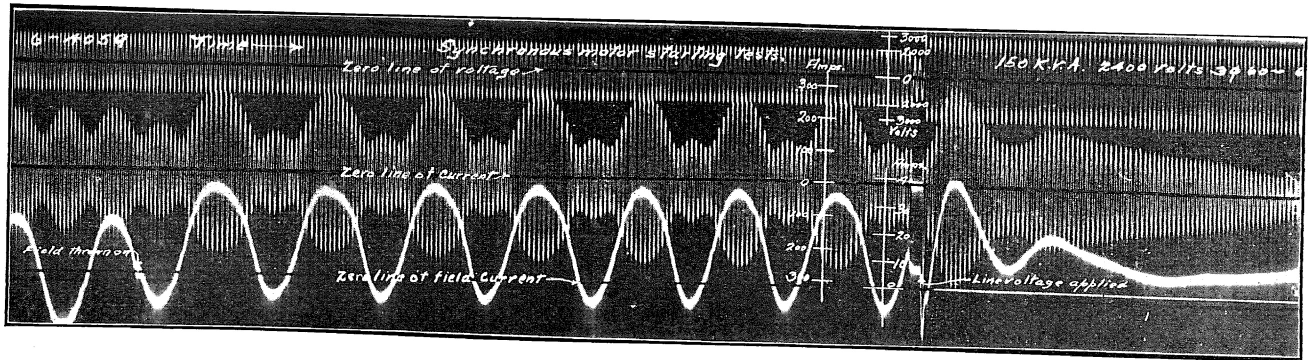
In practise the motor is usually in synchronism on the starting voltage, so that in the majority of cases over-excitation is the best condition.

It will be noted from the oscillograms that these large loads have been started and synchronized at the expense of excessive line currents. The maximum current amounts to 6.5 times the rated current of the motor with under-excitation and to 9 times with over-excitation. This large current is not objectionable, providing the motor rating is small compared with the generator capacity supplying it, and providing the motor winding and starting equipment have been designed with these large currents in view. It should also be borne in mind that the motor tested was not designed specifically for this service. This value of starting current could be materially reduced by modification of the design of the motor to approach more closely the usual design of an induction motor and by the use of reactance in the starting circuit. It will be noted that if the starting current is reduced by the insertion of reactance as an intermediate step between starting and line voltage, it will be necessary to reduce the current rush on application of excitation, if any material reduction in current is to be obtained, as the latter current is nearly as large as the current rush on application of line voltage. This, obviously, can be done by delaying excitation until the motor is running in synchronism on line voltage. While this method of starting and synchronizing was not tried with the 150-kv-a. motor used for the oscillograms shown, it has been tried with other motors and found successful. With a 200-kv-a. 6600-volt, 25-cycle 500-rev. per min. motor designed to drive a mine fan, the fan load amounting to 200 h.p. (represented on



[NEWBURY]

FIG. 27—MOTOR SYNCHRONIZED ON APPLICATION OF EXCITING CURRENT. $\frac{2}{3}$ STARTING VOLTAGE—35 AMPERES FIELD CURRENT. 88.7 KW. LOAD ON 150-KV-A. MOTOR



[NEWBURY]

FIG. 28—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE—15 AMPERES FIELD CURRENT. 139 KW. LOAD ON 150-KV-A. MOTOR

Original oscillogram was continued for ten seconds beyond the printed oscillogram so that there is no doubt that motor maintained synchronism.

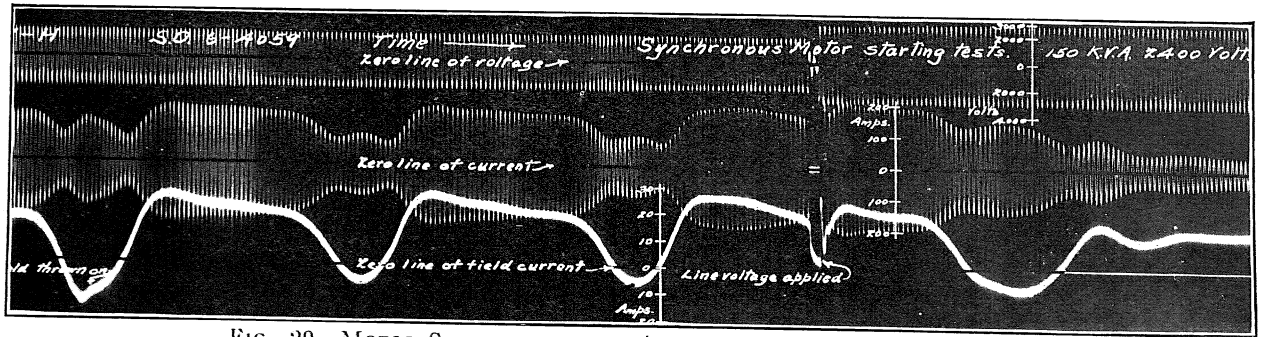
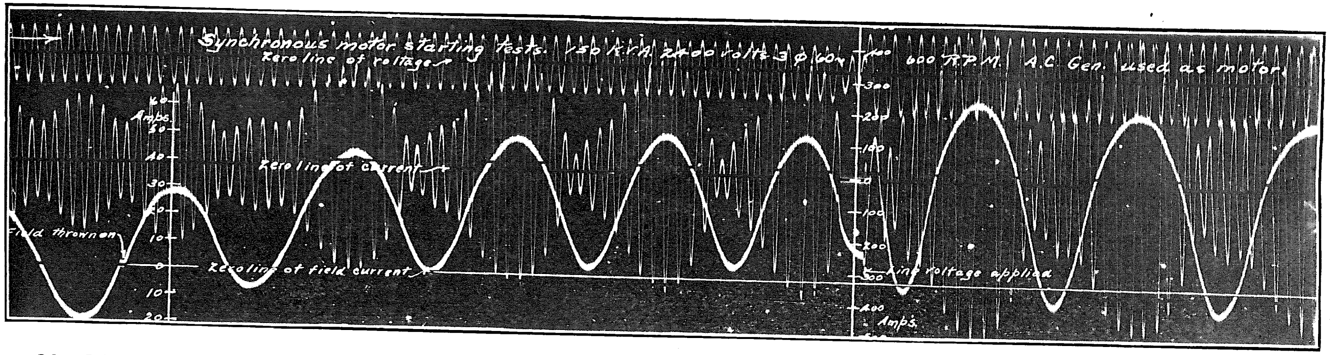


FIG. 29—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE [NEWBURY]

Same conditions as Fig. 28 except load is 112 kw.



[NEWBURY]

FIG. 30—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE. $\frac{2}{3}$ STARTING VOLTAGE — 35 AMPERES FIELD CURRENT 110 KW. LOAD ON 150-KV-A. MOTOR

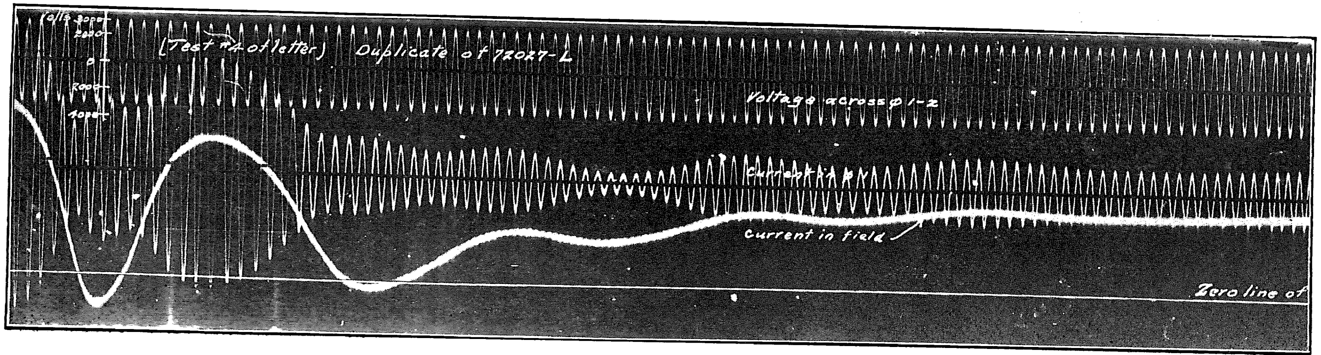


FIG. 30—(*Continued*)

test by a loaded d-c. generator) was started and synchronized with a maximum line current (measured by oscillograph) equal to 2.44 times the rated current of the motor. Without the reactance the current rush on changing from the starting voltage of 5000 volts to line voltage of 6600 was sufficient to trip the circuit breakers. While the current was not measured, the reactance clearly caused a large reduction in current.

The main facts in regard to synchronous motor starting as discussed in this paper form only a small part of the story that the oscillograms might tell, as the result of a complete and detailed analysis. The study the author has been able to give them has been, to the author, both interesting and profitable and independent study by other engineers will, it is felt, be well worth while.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

COMMUTATING-POLE SATURATION IN D-C. MACHINES

BY HAROLD E. STOKES

The saturation of the commutating pole is one of the principal factors upon which depends the satisfactory operation of d-c. commutating-pole machines. This is especially the case in such classes of machines as d-c. rolling mill motors, railway generators and other d-c. machines having to withstand heavy momentary overloads. Owing to the difficulty of measuring the fluxes combining to produce saturation, under normal working conditions, by other than sensitive laboratory tests, the designing engineer's knowledge of the phenomena attending the commutating-pole fluxes has lagged somewhat behind their application in commercial practise.

Tests have been made at various times, by different engineers, to ascertain the saturation of commutating poles, and as far as the author knows, a method of test employing the ballistic galvanometer has always been used. This is necessarily a test involving considerable refinement and can scarcely be considered a commercial test floor method. Hence, most designers have been satisfied with obtaining sparkless commutation, or if brush potentials gave them an approximate indication of the working saturation of the commutating pole.

A method of obtaining iron saturations and losses has been used by Dr. Gisbert Kapp for transformers and other stationary apparatus, which consists in varying the flux density by changing the excitation, and observing the time of change, the exciting ampere-turns and the voltage induced in an auxiliary coil enclosing the iron section carrying the fluxes to be investigated. This method has been adapted by the author for the

purpose of obtaining commutating pole saturations under normal working conditions. Satisfactory results have been obtained and owing to the method being devoid of the extreme refinement necessary to secure good results by the ballistic method, can frequently be employed by the ordinary test floor staff.

The machine to be tested has the armature fixed to prevent movement and the various windings—armature, series, shunt coils and commutating pole coils—connected for operation as a motor. The shunt coils are excited to their normal value of current. A coil consisting of a few turns of flexible wire is wound around the commutating pole at the point to be investigated, and the ends connected to a millivoltmeter.

By varying the current flowing through the commutating pole coils, a deflection is obtained on the millivoltmeter due to the varying flux at the part of the commutating pole embraced by the coil. By suitably varying the current through the machine so as to obtain an almost constant deflection on the millivoltmeter, observations of main current, millivoltmeter deflection and time in seconds, can be made. From these observations, the saturation of the commutating-pole at various loads and under working conditions can be calculated.

The determination of the best number of turns and resistance to be used in the exploring coil and the method of calculation are as follows:

$$e = T \frac{dN}{dt} 10^{-8} = T A \frac{dB}{dt} \cdot 10^{-8}$$

and

$$10^8 \frac{e}{T\ A} = \frac{dB}{dt}$$

Integrating, we have

$$\int_0^t 10^8 \frac{e}{T\ A}\ dt = \int_0^B dB$$

$$\frac{e}{T\ A} t\ 10^8 = B, \text{ and } t = \frac{BTA}{e\ 10^8}$$

$$e = \frac{BTA}{t\ 10^8}$$

Where e = Volts induced in exploring coil
T = Number of turns in exploring coil.
A = Cross-section area of commutating pole.
N = Flux linking exploring coil.
t = Time in seconds.
B = Flux density in commutating pole.

The approximate commutating-pole flux entering the armature is known to the designer and is of a dimension, say 500,000 c. g.s. lines. The commutating-pole section is say 100 sq. cm., giving $B = 5000$. A time of about 25 seconds is necessary to vary the main current from zero to the maximum value and obtain the necessary readings. A reading of two millivolts is assumed and the number of turns in exploring coil follows from the above formulas:

$$0.002 = T \times 100 \frac{5000}{25} \times 10^{-8}$$

$$T = \frac{0.002 \times 25 \times 10^{8}}{100 \times 5000} = 10$$

The resistance of the coil should be low enough so as not to absorb a large proportion of the induced volts in the exploring coil. The actual volts induced
e = millivoltmeter reading multiplied by

$$\frac{\text{resistance of millivoltmeter} + \text{resistance of exploring coil}}{\text{resistance of millivoltmeter.}} \quad \textbf{(1)}$$

Generally speaking, if the resistance of the exploring coil does not exceed about 0.2 to 0.3 ohms, while the resistance of a millivoltmeter reading 10 millivolts full scale reading, is 1.0 ohm, satisfactory results will be obtained even on small machines with a commutating-pole flux of small dimensions.

Formula (**1**) is based on a constant $\frac{\text{change of flux}}{\text{change of time}}$ giving a constant induced voltage in coil, but as in practise it is difficult to vary the current in the machine at such a rate as to give a constant change of flux with regard to time, it is sufficient if the current is varied at such a rate as to enable the operator to obtain steady voltage readings, taking periodically every three seconds simultaneous readings of current and time.

Connections are made as in Fig. 1; the shunt coils are separately excited to normal value and a booster capable of giving three or four times full load current is used to supply current to the machine undergoing the test. The current is varied at a suitable rate by means of a rheostat in the booster field, which is separately excited. With the exploring coil around the tip of commutating-pole, starting from zero, increase the current through the machine at a suitable rate; take readings as described above until, as the commutating-pole approaches saturation, the millivoltmeter reading begins to decrease.

At the point where the commutating-pole flux entering the armature reaches a maximum value, the millivoltmeter will be reading zero and any increase in the load current will result in a decrease in the flux entering the armature and threading the exploring coil. This decrease will produce a reverse reading in the millivoltmeter.

A complete set of positive and reverse readings should be taken until the load current is carried as high as conditions will permit. The change of flux can be calculated for each set of readings taken, from formula (**1**), by substituting time in seconds between each reading and volts obtained on the millivoltmeter. From the summation of the fluxes thus obtained, a saturation curve can be plotted, showing flux and exciting ampere-turns.

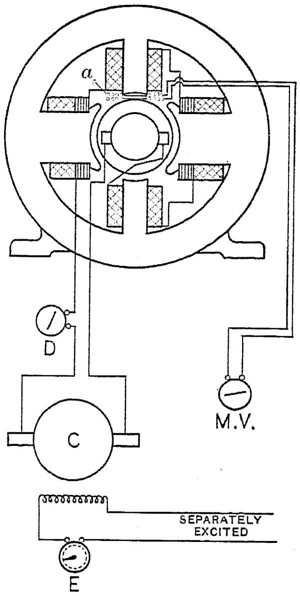


FIG. 1

A. Exploring coil.
M.V. Millivoltmeter, double reading.
C. Booster capable of supplying current to required limit and with field separately excited.
D. Ammeter in series with armature, series and commutating coils.
E. Booster shunt field rheostat.

Fig. 2 shows a saturation curve (a) taken at the commutating-pole tip while curve (b) shows commutating-pole saturation at the junction with the frame. To obtain curve (a), the load current was increased until the direction of the interpole flux entering the armature was reversed at point X, due to the commutating-pole ampere-turns being all absorbed in balancing the armature ampere-turns and in pushing the leakage flux through the commutating-pole. To obtain curve (b), the exploring coil

was placed round the commutating-pole as near to the magnet yoke as possible. Readings were taken as for curve (a). The leakage ratio, at any load, is given by $\frac{b-a}{a}$ and is practically constant until the flux approaches the knee of the saturation curve.

While it is of only secondary importance to know the point in the load at which the useful flux becomes zero, it is of great importance to be able to predetermine the useful flux at the maximum overload at which the machine is to operate. Satisfactory commutation at the maximum overloads is dependent on a reasonably accurate predetermination of the useful commutating-pole flux.

Fig. 3 shows the ampere-turns on the commutating-pole available for driving the useful flux into the armature. $O\ B$

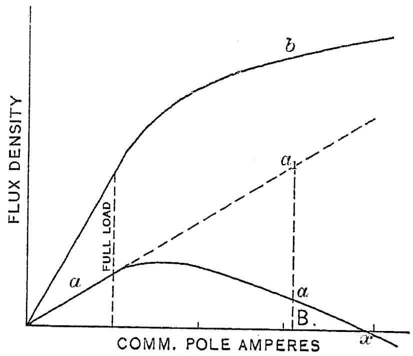


FIG. 2
Curve (a) shows useful commutating pole flux entering armature.
Curve (b) shows commutating pole flux against yoke.

shows commutating-pole ampere-turns plotted against load current.

With a ratio

$$\frac{\text{commutating-pole ampere-turns}}{\text{armature ampere-turns}} = 1.5,$$

$O\ A$ represents armature ampere-turns at any load. The horizontal length between $O\ B$ and $O\ C$ shows the ampere-turns taken to push the useful and leakage flux through the commutating-pole iron; thus, at full load, the iron ampere-turns are almost zero, while at two and one half times full load the iron ampere-turns are represented by $A''\ B''$.

The excess of commutating pole over armature ampere-turns, is given at full load by $D'\ B' - D'\ A' = A'\ B'$, and as the iron ampere turns are negligible, the full amount $A'\ B'$ is available

to push the useful flux into the armature. At two and one half times full load the iron ampere-turns are shown by $C''\ B''$ and are equal to the excess ampere-turns $A''\ B''$. At this point in the load, the ampere-turns required to balance the armature ampere-turns are given by $D''\ A''$, and the excess is all absorbed in pushing leakage flux through the commutating pole, so there is left zero ampere-turns to push useful flux into the armature. At this point, therefore, the useful flux becomes zero, and corresponds to point X in Fig. 2. At loads greater than two and one half times full load, the ampere-turns to push the leakage flux through the commutating pole exceed the excess ampere-turns and there are insufficient ampere-turns to balance the armature; in consequence the direction of the useful flux is reversed.

Fig. 3 is useful in obtaining a clear conception of the forces

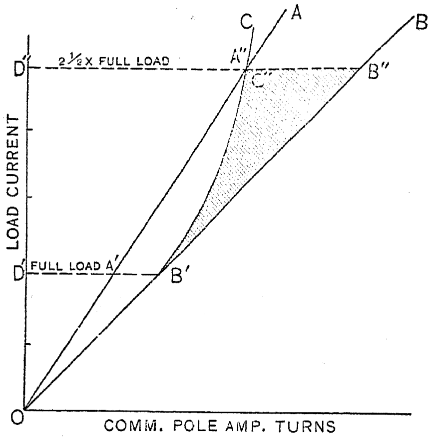


FIG. 3

acting at various loads to produce the useful flux for commutation; the length $A'\ B'$ may be considered as representing reactance volts at full load due to the reversal of the current in the armature coils undergoing commutation. The shaded area shows, at any load, the uncompensated reactance volts, and this figure should not exceed the permissible value for successful operation at the maximum overload at which the machine is to operate.

Tests made on machines of different characteristics show a wide difference in the point X (Fig. 2) at which load current the reversal of the useful commutating-pole flux takes place. An eight-pole generator designed for normal overload capacity showed the reversal point X occurring at about four times full load current, while a six-pole machine showed the useful flux to

be still about 70 per cent of its maximum value at a load of five times full load; the reversal point X would probably not occur until a load current of 10 to 12 times full load current was reached.

In Fig. 2, the dotted line $a\ a'$, drawn through the straight part of curve (a), the useful flux, represents, in its ordinates, the reactance volts at any load, thus $a'\ B - a\ B$ gives the uncompensated reactance volts, to a certain scale, correspending to the load b. It is therefore important that the actual curve $a\ a$ should lie along the straight line $a\ a'$ within the limits of operation of the machine. The part $a'\ a$, representing the dimension of uncompensated reactance volts, should not be greater than experience shows to be the maximum for reasonably sparkless commutation.

A consideration of Fig. 2 shows that the surprising difference at which the point X occurs, in six- and eight-pole machines, is due mainly to the leakage ratio R, at the straight part of the leakage and useful curves occurring at light loads. This ratio is termed the initial leakage ratio throughout the following discussion. In the eight-pole machine, the initial leakage ratio was found to be about 2.15, while the six-pole machine gave a figure of 1.0.

The symbols given are used in the following discussion.

B_u = Useful flux density in air gap of commutating pole.

B_l = Leakage flux density in commutating pole at yoke.

B_t = Total flux density in commutating pole at yoke $= B_u + B_l$

K_u = Coefficient of useful flux = gap length $\times$ 0.8 $\times$ gap. coefficient.

K_l = Coefficient of leakage flux = effective leakage gap length $\times$ 0.8.

$A.\ T.$ = Ampere-turns.

$A.\ T_e$ = Total ampere-turns on commutating pole minus armature ampere-turns

$A.\ T_a$ = Ampere turns for pushing leakage flux across effective leakage space.

$A.\ T_t$ = Total commutating pole ampere-turns.

$A.\ T_i$ = Total iron ampere turns for useful and leakage flux.

$$R_l = \frac{A\ T_t}{A\ T_e}$$

$$= \frac{\text{Total commutating pole ampere-turns}}{\text{Total commutating pole ampere turns} - \text{armature ampere turns}}$$

Fig. 2 shows that until some degree of saturation is reached in the commutating pole, the curves showing the useful and total flux are straight line curves, and hence the leakage flux, *i.e.*, total flux minus useful flux, is also a straight line curve for so long as the total and useful curves are straight. It is therefore evident that the leakage gap can be represented by a certain definite equivalent gap length with the total ampere-turns as effective over that gap length. The above symbol K_l is thus obtained:

$$A.\,T_a = B_l \times K_l, \text{ and } K_l = \frac{A.\,T_a}{B_l}$$

For the purpose of this discussion, it is assumed that the commutating-pole is of uniform section from tip to junction with the yoke and therefore B_u in gap will also be of the same dimension as B_u in the pole.

$$A.\,T_t = K_l\,B_l + A\ T_i$$

and

$$A.\,T_e = K_u\,B_u + A\ T_i = \frac{A.\,T_t}{R_l}$$

substituting for $A\ T_t$, and

$$\frac{K_l\,B_l + A\ T_i}{R_l} = K_u\,B_u + A\ T_i$$

$$K_l\,B_l + A\ T_i = R_l\,K_u\,B_u + R_l\,A\ T_i, \text{ and } B_l = B_t - B_u$$

Therefore

$$K_l\,B_t - K_l\,B_u = R_i\,K_u\,B_u + R_l\,A\ T_i - A\ T_i$$
$$K_l\,B_u + R_i\,K_u\,B_u = K_l\,B_t - R_l\,A\ T_i + A\ T_i$$
$$B_u\ (K_l + R_i\ K_u) = K_l\,B_t - A\ T_i\,(R_l - 1)$$

$$B_u = \frac{K_l\,B_t - A\ T_i\,(R_l - 1)}{K_l + R_l\,K_u} \qquad (1)$$

With known values of K_l, K_u and R_l, the formula becomes simply

$$B_u = (X)\ B_t - (Y)\ A\ T_i$$

By assuming a series of values for B_t, the corresponding values

of B_u can be directly determined. The values of load current corresponding to values of B_u can then be obtained.

$$A\ T_a = B_l \times K_l$$

where

$$B_l = B_t - B_u$$

$$A\ T_t = A\ T_i + A\ T_a$$

$$\text{and load current} = \frac{A\ T_t}{\text{commutating-pole turns.}}$$

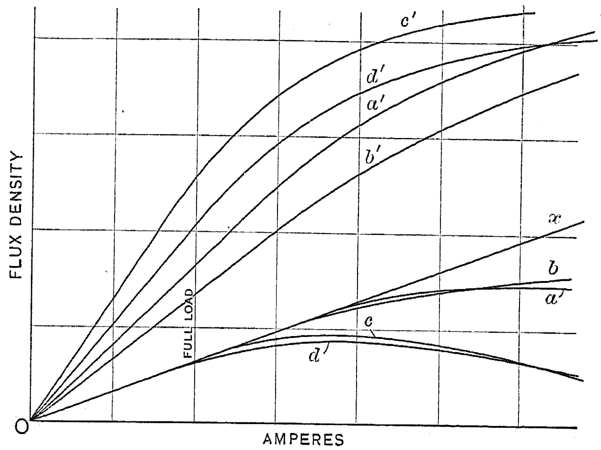


FIG. 4

Curves $a\ a'$.....$Kl = 2.2$, $Ku = 1.53$, $\dfrac{\text{Comm. pole } A.\ T.}{\text{Armature } A.\ T.} = 1.9$

Curves $b\ b'$.....$Kl = 2.2$, $Ku = 0.645$, $\dfrac{\text{Comm. pole } A.\ T.}{\text{Armature } A.\ T.} = 1.35$

Curves $c\ c'$.....$Kl = 1.1$ $Ku = 1.53$, $\dfrac{\text{Comm. pole } A.\ T.}{\text{Armature } A.\ T.} = 1.9$

Curves $d\ d'$.....$Kl = 1.1$, $Ku = 0.645$, $\dfrac{\text{Comm. pole } A.\ T.}{\text{Armature } A.\ T.} = 1.35$

From the machines tested, the values of R_l, K_u and K_l were obtained. These values were substituted in formula (**1**) and values of B_u and B_t obtained and plotted against the load current. The tested and calculated values of B_u agreed pretty closely. In making the calculation, the $A\ T_i$ were taken for a uniform density along the full length of pole, and even with this approximation, the calculated B_u did not differ more than 13 per cent from the tested figure up to a load of about four times full load current.

Fig. 4 shows a series of calculated curves plotted for the eight-pole machine tested, with varying values of initial ratio, R, K_l and K_u. From these curves it is seen that the dimension of K_l is the principal factor in keeping the useful flux B_u along the straight line drawn through the initial useful flux line. Thus if K_l is low, the curve showing B_u will fall away from the straight line representing reactance volts, marked x in Fig. 4, at lower values of load current than for high values of K_l. These curves also show that R_l, or stated in another way, the ratio

$$\frac{\text{commutating-pole } A\ T}{\text{armature } A\ T}$$

has little effect in maintaining the curve B_u along the straight line x. Curves $a\ a'$ and $b\ b'$ show the useful and total commutating pole flux with $K_l = 2.2$ and $K_u = 1.53$ and 0.645 respectively. The useful flux curve sticks closely to the line $O\ X$ representing reactance volts up to a point corresponding to twice full load current. The curves $c\ c'$ and $d\ d'$ show the useful and total flux with $K_l = 1.1$ and $K_u = 0.645$ and 1.53 and giving ratios of $\frac{\text{commutating-pole } A.\ T.}{\text{armature } A.\ T.} = 1.35$ and 1.9 respectfully. In both these cases the useful flux curve drops off rapidly at about 1.45 times full load current. The usefulness of the higher ratios $\frac{\text{commutating-pole } A.\ T.}{\text{armature } A.\ T.}$ is offset by the increased initial ratio of $\frac{\text{leakage flux}}{\text{useful flux}}$

In using the formula

$$B_u = \frac{K_l\, B_r - A\ T_i\,(R_l - 1)}{K_l + R_l\, K_u}$$

to ascertain the commutating characteristics of a new design at the maximum operating loads, it is necessary to obtain the values of K_u and K_l; the former may be readily figured as given above, $K_u = l_g \times 0.8 \times K_g$

Where l_g = commutating-pole gap length in cm.

K_g = gap coefficient as obtained by Carter's or Arnold's method.

To determine the dimension of K_l, a consideration of the paths taken by the commutating-pole and main pole leakage and their dependence on the relative magnetomotive forces producing them, is necessary. It has been shown* that the useful armature fluxes due to the main and commutating-poles in any part of the iron circuit, are given by the algebraic sums of the values of

$$\frac{\text{magnetomotive forces}}{\text{reactance}}$$ producing the flux in the path under consideration.

Figs. 5 and 6 show the distribution of the useful fluxes in the magnetic circuits of a two-pole machine with commutating poles. Fig. 5 shows the main poles excited while the commutating

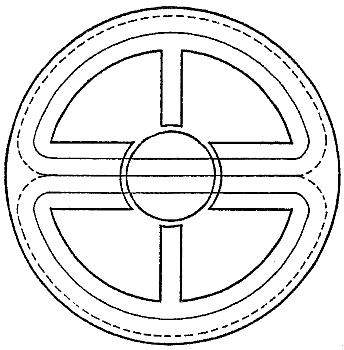


FIG. 5

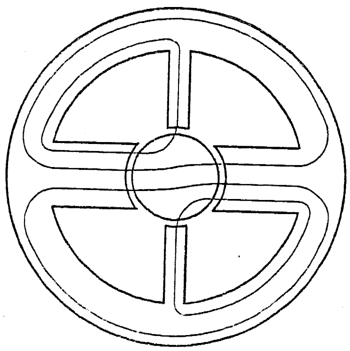


FIG. 6

poles are unexcited. Three lines are shown in the main air gap, a dotted line representing one-half line. Fig. 6 shows the same excitation of the main poles and in addition the commutating poles are excited so that there is one line in the commutating-pole air gap.

These figures show that the part of the frame forming a path common to the main and commutating-pole flux has its flux density increased by one-half of the commutating-pole flux, when the commutating-pole is excited; that part of the frame forming a path not common to the main and commutating-pole flux has the flux density reduced by one half of the commutating-pole flux.

By applying a similar process of reasoning, it can be shown that the main and commutating-pole leakage fluxes follow a distribution closely similar to that of the useful fluxes.

* Brunt in *Electrical Review and Western Electrician*, Sept. 9, 1911, p. 514.

In Fig. 7, the leakage paths of main and commutating poles are shown, the magnetomotive forces being represented by E and e for main and commutating poles respectively. The flux and reluctances of the various paths are represented by I, R and r. Applying Ohm's and Kirchoff's laws, the fluxes in the various paths, with an assumption of a constant reluctance will be as given below.

With only main poles excited

$$I_1 = \frac{2\,E}{2\,R_1 + R_2 + R_3}$$

$$I_2 = I_3 = I_4 = I_5 = \frac{E}{2\,R_1 + R_2 + R_3}$$

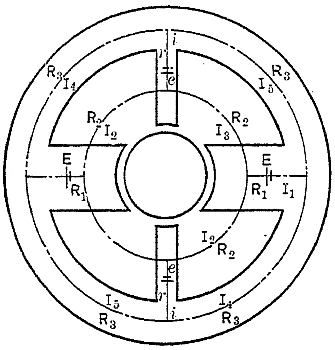


FIG. 7

With only commutating poles excited

$$i = \frac{2\,e}{2\,r + R_2 + R_3} \tag{1}$$

and

$$I_2 = I_3 = I_4 = I_5 = \frac{e}{2\,r + R_2 + R_3} \tag{2}$$

With both main and commutating poles excited.

Since the effect of the two main poles on the commutating poles is to neutralize one another as is also the effect of the two commutating poles in regard to the main poles, then the flux in the commutating poles and main poles will be the same for the same excitation, as for the cases considered with main and com-

mutating poles individually excited without the other. The flux in the leakage paths between poles is given by the following:

$$I_2 = I_4 = \frac{E}{2\,R_1 + R_2 + R_3} + \frac{e}{2\,r + R_2 + R_3} \tag{3}$$

$$I_3 = I_5 = \frac{E}{2\,R_1 + R_2 + R_3} - \frac{e}{2\,r + R_2 + R_3} \tag{4}$$

A comparison of formulas **1**, **2**, **3** and **4** shows that the leakage flux after the introduction of the commutating-pole excitation, is increased in the paths common to both main and commutating-pole leakage, by one half of the commutating-pole leakage. In the paths not common to both fluxes, the flux is decreased by one-

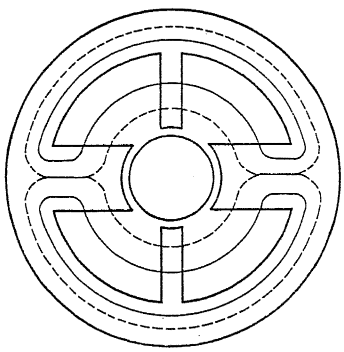


FIG. 8

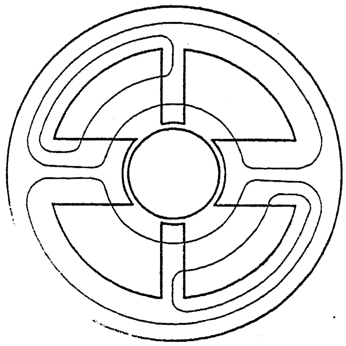


FIG. 9

half the commutating-pole leakage flux. The distribution of the commutating-pole leakage flux is therefore very similar to that of the useful flux.

Figs. 8 and 9 show the distribution of three leakage lines before and after the commutating pole is excited. Compare these with Figs. 5 and 6 showing the distribution of the useful armature flux.

At low saturation, R_1, r and R_3 may be neglected and equations **3** and **4** become

$$I_2 \text{ and } I_4 = \frac{E}{R_2} + \frac{e}{R_2} = \frac{E + e}{R_2}$$

$$I_3 \text{ and } I_5 = \frac{E}{R_2} - \frac{e}{R_2} = \frac{E - e}{R_2}$$

The main pole leakage becomes

$$I_1 = \frac{2\,E}{R_2}$$

The commutating pole leakage becomes

$$i = \frac{2\,e}{R_2}$$

At a point in the load where $E = e$, and assuming that the leakage paths of the main and commutating poles have the same reluctance, the leakage is all absorbed by the commutating pole. Fig. 10 represents the leakage flux distribution for this condition. If the machine under consideration is shunt or com-

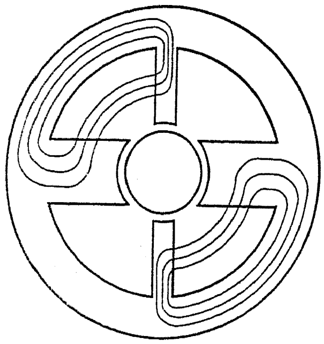


FIG. 10

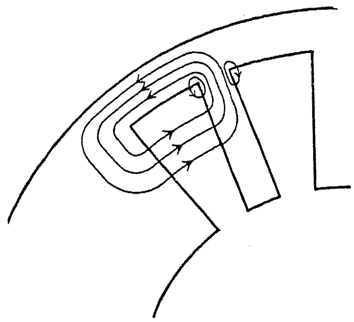


FIG. 11

pound-wound, a further increase in the load current would give $e > E$. As in all normal designs, the total main flux is considerably in excess of the commutating pole fluxes, the distribution of the leakage flux will always be similar to that shown on Fig. 11, *i.e.*, the commutating pole fluxes will take a path through one of the adjacent main poles and will not travel completely round the magnet frame to the next commutating pole. Thus at loads when $e > E$, the commutating pole leakage comprising the excess of commutating pole leakage over main pole leakage must take a local path as shown in Fig. 11.

Some leakage taking a local path, however, exists before the point in the load is reached, at which $e > E$.

Fig. 12 shows a two-pole commutating pole machine, having a mean air leakage path of $2\,l$ or l per pole. The mean leakage path to the frame is l_1.

At a point A in the frame, there will be a leakage due to the left-hand pole, proportional to

$\frac{A.\,T.}{l_1}$, where $A.\,T.$ = ampere-turns per pole. Due to the right-hand pole there will be a leakage to A, proportional to $\frac{A.\,T.}{l_2}$ but in the opposite direction to leakage due to left-hand pole. Hence the actual leakage in path l_1 will be proportional to

$$\frac{A.\,T.}{l_1} - \frac{A.\,T.}{l_2} = A.\,T.\,\frac{l_2 - l_1}{l_1\,l_2}$$

In a two-pole machine, the difference between the lengths l_1 and l_2 is much greater than the difference existing in say a twelve-pole machine. On this account the local leakage or leakage direct to the frame, will be generally much greater in machines with a low number of poles, than in machines having a high number, the same ampere-turns per pole and length of local leakage path l_1, prevailing in either case. This effect is, however, more than overbalanced by the decreased length of the path l, and the consequent increase of leakage direct to the pole occurring in machines having a high number of poles.

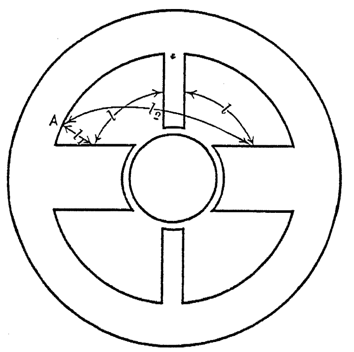


FIG. 12

The local pole leakage will have, in addition to path l, paths l_3 at the ends of the pole, toward the commutator and rear end. This leakage will also be modified by the adjacent pole as described above in connection with the local leakage at the sides.

The local leakage paths should generally be treated separately and summed up into a single expression

$$N_l = \frac{A.\,T.}{l_l}$$

N_l = local leakage per commutating pole.
N_d = direct pole to pole leakage per commutating pole.

N = total leakage $= N_l + N_d$
N_m = direct main pole leakage per pole.
$A.T.$ = ampere-turns per commutating-pole.
l_l = mean corrected length of the local paths.
l_d = mean length of direct pole to pole paths.

The direct commutating pole leakage, *i.e.*, pole to pole leakage, may be treated in a similar manner, a number of paths plotted and a resultant expression obtained:

$$N_d = \frac{A.T.}{l_d}$$

The total leakage per pole, before saturation is reached, will then be given by the expression, $N = N_l + N_d$.

It does not necessarily follow, even before saturation occurs in the iron parts of the leakage path, that N will be proportional to the $A.T.$ of the commutating pole as there are other factors exercising an influence. Consider a shunt machine; at light loads $e < E$, and, assuming no saturation in the iron parts of the leakage path, the direct leakage N_d, is proportional to the ampere turns on the pole; this statement also applies to the local leakage N_l. At load where $e > E$ the direct leakage N_d will remain stationary while N_l will increase proportionally with the load and ampere turns on the commutating-pole. Further, it may happen that the main pole leakage taking the low resistance path through the commutating-pole, has the effect of producing some degree of saturation in the commutating pole. In cases of normally designed machines, it does not seem that this factor has much influence, however.

From the above it is seen that there may be two different dimensions of initial leakage, the earlier one, in point of load, being given by the expression

$$N = \frac{A\ T}{l_l} + \frac{A\ T}{l_d}$$

The second dimension occurring after a point in the load has been reached where the commutating pole leakage is greater than the main pole leakage, will be given by

$$N = \frac{A\ T}{l_l} + \frac{A\ T_b}{l_d}$$

Where $A\ T_b$ = the commutating pole ampere-turns at a load where the direct commutating pole leakage balances the direct main leakage; thus in a shunt machine, the latter part of the formula $\left(\frac{A\ T_b}{l_d}\right)$, will be a constant at all loads higher than that at which the balance between direct main and commutating pole leakage is reached.

To obtain close results when figuring the value of B_u from the formula

$$B_u = \frac{K_l B_t - A\ T_i (R_l - 1)}{K_l + R_l K_u}$$

it is therefore necessary to obtain two values of K_l, one for $N < NM$ and the other for $N > N_m$. K_l will always have two values, excepting the case of a series-wound machine, when N/N_m will have an almost constant relation.

It was previously stated that the commutating pole ampere-turns, $A\ T_i$, were taken for the density at the root of the pole, in using the formula for B_u. This, obviously, is not quite correct, as the density tapers off towards the armature; however, from the author's experience, a comparison of calculated and test results appears to show sufficiently near results to justify the approximate method.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 25, 1913.

CONSTANT VOLTAGE TRANSMISSION

BY H. B. DWIGHT

For deciding upon the method of operation of a transmission system, two distinct alternatives are presented, one of which has been brought forward but recently. In the older method, which is the one in common use, the voltage of the system is controlled entirely from the generators. The chief disadvantage is the large variation in voltage, which is indeed the factor limiting the carrying capacity of the system. In the newer method, there is no voltage variation at all, this result being obtained by controlling the voltage from both the generating end and the receiving end. The newer method also increases several fold the carrying capacity of a transmission line. This new constant-voltage method has been used successfully in commercial operation, though as yet only on small systems. It offers large advantages both in better service and in lower cost, over the usual varying-voltage method.

It is proposed to make a comparison in the following paragraphs between the two methods, dealing especially with the reduction in cost made possible for large power systems, the reliability of the new method, and the ways in which the new method of operation may influence the design of transmission systems.

The method in common use with transmission lines needs but little description as it consists merely of controlling the voltage on the line by adjusting the voltage of the generators supplying the power. Since at no-load the two ends of the line are at approximately the same voltage, while under load there is considerable drop at the receiver end, a variation in voltage is unavoidable as the load increases or decreases. This variation

may take place at the generator end or the receiver end, as desired, but in either case it puts a limit on the amount of power which the line can transmit. A system which delivers electric power to a customer at a voltage varying 10 or 15 per cent throughout the day is not considered to be giving good service, as the operation of lights and motors is seriously interfered with. Therefore when the load on a transmission system becomes so large as to produce too great a variation in voltage for good service, it has been the customary practise to build additional transmission lines, or to adopt a higher line voltage. It is at this stage that constant-voltage transmission appears most attractive, as it provides greatly increased carrying capacity without any alterations in the transmission line itself.

The constant-voltage method of control is radically different from the usual method. Instead of controlling the voltage from one end only, special machinery consisting generally of synchronous motors or synchronous condensers is installed at the receiver end, and the voltage is controlled at that end also by adjusting the power factor. Enough synchronous motors are installed to keep the voltage at a steady value at both the receiver end and at the generator end.

The way in which the synchronous motors operate to hold the voltage constant is very similar to the way in which they are frequently used to improve the power factor of a load. It is well known that a large part of the voltage drop in a transmission line is due to the line reactance. The reactance drop is greatest when the load has a low power factor, and it is, in fact, directly proportional to the lagging reactive component of the load. The drop is therefore changed into a rise in voltage if the reactive component is leading instead of lagging, and this may be sufficient to overcome the drop due to resistance. This is expressed in symbols as follows:

Let R be the resistance of the line and X the reactance. Let P be the in-phase component of current and Q, the lagging reactive component. Then the drop in voltage is approximately

$$PR + QX$$

or, more exactly,

$$PR + QX + \frac{(PX - QR)^2}{2(E + PR + QX)}$$

where E is the voltage at the receiver.

If now Q is made negative, that is, if it is a leading current, QX opposes the drop PR and tends to neutralize it. The quantity Q can be controlled by adjusting the field current of the synchronous motors, since with a strong field the motors will operate with a leading current. It is therefore possible to control the voltage at the receiver end by adjusting the field current of the synchronous motors. This adjustment must be under the control of the transmission line operators in order to have the correct effect on the line voltage.

In water-power plants the voltage and also the frequency are subject to sudden changes due to variations in load which are too rapid for the waterwheel governors to compensate for immediately. In such cases a large flywheel effect on the system tends to minimize this trouble. Synchronous motors add directly to the flywheel effect and are found very useful in this way.

The advantages obtained from the use of synchronous motors by maintaining constant voltage at both the generator and receiver ends of the line and by adding to the flywheel effect, have been sufficient to warrant their installation on several short transmission systems. In such cases the improvement in the service given to customers at all parts of the system justified the additional expense. But when it is stated that the synchronous motors must be equal to one-half or two thirds of the generator capacity the cost will at first sight seem prohibitive for most cases. In consideration of this, the additional fact must be taken into account that the newer method not only improves the service, but very greatly increases the carrying capacity of the line. Since with a line of about 100 miles (160 km.) in length the cost of the generators is comparatively small compared with the cost of the line, the installation of synchronous motors will actually save money in large systems, by saving extra line construction.

The limit of carrying capacity is ordinarily set by the maximum variation in voltage allowed for good service, that is, by the regulation of the line. But if there is no voltage variation at all, another limit must be looked for, and this will be found in the greatest energy loss which can be allowed for the transmission. Power for supplying line losses costs very little in most systems, so that an efficiency of 85 per cent is generally consistent with good economy. The curves of Figs. 1 and 2 for constant-voltage lines have been plotted for this value of

efficiency. A glance at these curves shows that the carrying capacity of a 25-cycle line can be doubled by adopting the constant-voltage method, and the capacity of a 60-cycle line can be multiplied by two or three.

It is shown in the diagram, Fig. 5, that there is a maximum amount of power for a constant-voltage line, which cannot be exceeded under any conditions without raising the voltage, no matter how low the efficiency is allowed to become, nor how much synchronous machinery is installed. This has been pointed out by Mr. Philip, and a diagram given for the case where

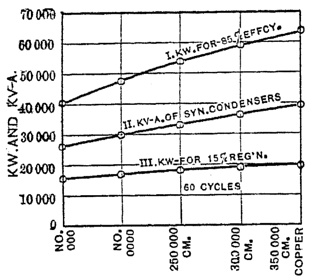


FIG. 1

I. Carrying capacity for transmission lines at constant voltage.

II. Synchronous condensers required.

III. Carrying capacity for transmission lines at varying voltage.

Length of lines, 100 miles. Highest voltage on lines, 115,000 volts. Efficiency and regulation calculated for line alone, without additional reactances.

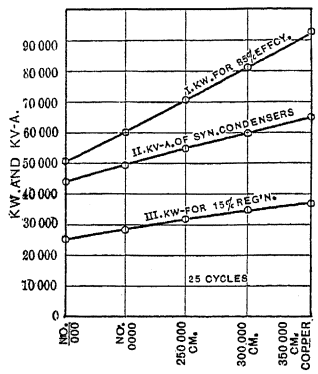


FIG. 2

I. Carrying capacity for transmission lines at constant voltage.

II. Synchronous condensers required.

III. Carrying capacity for transmission lines at varying voltage.

Length of lines, 100 miles. Highest voltage on lines, 115,000 volts. Efficiency and regulation calculated for line alone, without additional reactances.

the receiver voltage is equal to the generator voltage.* The practical limit to the carrying capacity of a line is smaller than the above maximum, due in most cases to the energy loss becoming excessive and to the rapid increase in the amount of synchronous condensers required. The present paper therefore uses as a practical limit a moderate percentage of loss, such as corresponds to about 85 per cent efficiency.

The saving in cost effected by the constant-voltage system increases very rapidly as the number of miles of line becomes

*R. A. Philip, *Economic Limitations to Aggregation of Power Systems.* TRANS. A. I. E. E., 1911, p. 612.

greater. The curves of Fig. 3 show that for 60 cycles, the cost of a constant-voltage line with the necessary synchronous motors represents a saving when the length is over 70 miles (112 km.). For 25 cycles, Fig. 4, the saving over the varying-voltage method is not obtained until the length is 120 miles (193 km.) or more. As noted elsewhere, no allowance has been made for cost of land, owing to the extreme variableness of this item. If this were included, the constant-voltage curves would show more favorably. On the other hand, no allowance has been made for the cost of power for line losses, which are greater for the constant-

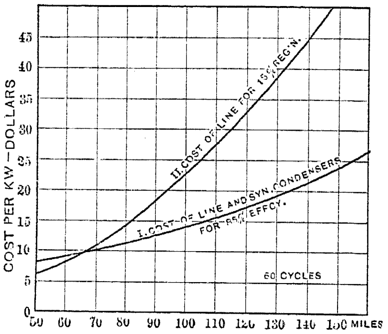


FIG. 3

I. Cost per kw. of transmission line and synchronous condensers, constant voltage.
II. Cost per kw. of transmission line, varying voltage.
250,000 cir. mil copper conductors. 115,000 volts, highest voltage on lines.

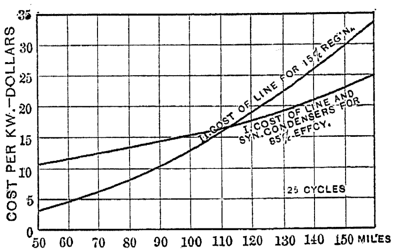


FIG. 4

I. Cost per kw. of transmission line and synchronous condensers, constant voltage.
II. Cost per kw. of transmission line, varying voltage.
250,000 cir. mil copper conductors. 115,000 volts, highest voltage on lines.

voltage lines used in calculating the curves than for the corresponding varying-voltage lines.

The costs as plotted are merely approximate, and are not intended to give an actual estimate of what a transmission line would cost. The curves are presented rather to show the effect on the cost, of changing certain factors such as size of conductors, length of line, and method of control.

The comparisons in Figs. 3 and 4 are not quite complete, owing to another saving in cost which is possible when designing a line for constant-voltage work. This saving is made by using large conductors. The cost curves show that with an existing line of considerable length it pays to install synchronous motors if enough power is to be transmitted to utilize the line to its full

capacity on the new basis. As may be noted from the first two figures, the increase in carrying capacity, and therefore the saving in cost per kilowatt, is greatest when large conductors are used. In ordinary transmission there is practically no advantage in using a larger conductor than about No. 0000 copper for 60 cycles. Reducing the resistance to a value less than one-third of the reactance does not materially improve the regulation, which is determined under these conditions almost entirely by the reactance. But with constant-voltage operation, a large proportion of reactance to resistance within a certain limit is no longer a hindrance, and so large conductors can be used to good advantage. This increases the carrying capacity of the line at small extra cost.

It may be mentioned as a minor consideration that a line with large conductors will have a comparatively small amount of corona loss, and so it may be operated at a higher voltage than where smaller conductors are used.

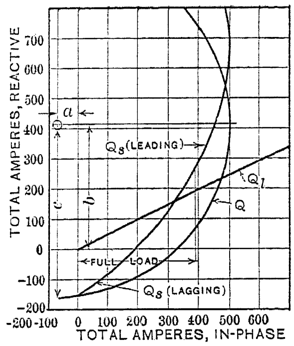


Fig. 5—Diagram, 200-Mile Constant Voltage Line. Charging Current Neglected

It was pointed out that high reactance is a detriment to a line operating with varying voltage but is not such a great disadvantage when the constant-voltage method is used. For instance, Figs. 1 and 2 show that a smaller proportion of synchronous motors is needed with a 60-cycle line than with a 25-cycle line. This is due to the higher reactance of the 60-cycle line. Now the reactance used in estimating the curves has been merely the reactance of the line. The reactance of the entire circuit includes that of the generators, step-up transformers, protective reactance coils, and step-down transformers, as well as the line reactance. Of late years it has been customary in large systems to make all these reactances as large as possible for protective reasons, in spite of the fact that they tend to make the regulation poor, and so limit the power which can be transmitted. High reactances give protection by reducing short-circuit currents, which are tremendous in large power stations and are very destructive both in their heating effects and in the mechanical distortions which they produce in the apparatus. High reactance in the reactance coils placed between the line and the station

apparatus gives very effective protection against abnormal voltages due to lightning, and to surges caused by switching. It is evident that with constant-voltage transmission it will be economical to increase all these reactances much beyond the values in use at present, and better protection will thus be obtained. It may therefore be stated that the possibility of using high reactance in all the various kinds of apparatus connected with the system, is one of the most important points in favor of constant-voltage transmission.

It may safely be stated that the reason why the frequency of 25 cycles was adopted to any extent in this country was because its low reactance made it more economical for transmission. This is shown by the curves of Figs. 3 and 4. The same figures show that with constant voltage, the frequency of 60 cycles becomes as economical as 25 cycles. With the exception of railway work, the frequency of 60 cycles is preferable for most important applications of electric power, especially the supply of power to large cities. The cost of generators, transformers, and motors is generally less at 60 cycles, and the operation of most lighting devices, especially tungsten lamps and arcs, is much more satisfactory at the higher frequency. Any method, therefore, which tends to make 60-cycle transmission more economical than 25-cycle, should be welcomed, as it will assist in standardizing the electric machinery of the country at the single frequency of 60 cycles.

The most advantageous application of constant-voltage transmission is probably not in transmission lines with a single generating station, but rather in large transmission networks connecting all the hydroelectric plants and the cities within a radius of several hundred miles. The generators placed at various points of the network themselves partly take the place of the synchronous motors for maintaining constant voltage, and thus the total capacity of synchronous motors required is somewhat less. Duplicate lines for use as reserves in case of breakdown are not required as much in networks as in straight transmission projects, since power can generally be supplied to any point from more than one direction. Thus a small number of heavy lines can be used in networks, and constant-voltage operation is especially applicable to these. All the advantages of low cost, good service, and good protection which have been described for constant-voltage transmission lines, are to be obtained with a large transmission network operated with steady voltage at both generating and receiving stations.

Very large transmission networks have already grown up, and are steadily increasing in extent. The engineering advantages of combining small power systems into one large network are due to the combination of differing load curves, water storages, reserves in case of breakdown, and even differences in standard time, etc. These have been discussed so thoroughly that they need only be mentioned here. The principles of constant-voltage transmission can greatly increase the economy and range of operation of large transmission networks. It does not seem unreasonable in view of the already rapid growth of many of these systems, to state the possibility of a single high tension network for the supply of power over the entire country.

When larger transmission networks are advocated it might be objected that the limit has been already reached of the number of generating stations which can be connected to one network, owing to the danger from such large amounts of generator capacity when a short circuit occurs. But a network which is operated at constant voltage contains an unusually large proportion of reactance, both in the line and in the station apparatus. Thus when a short circuit occurs the voltage drop toward the short circuit is very rapid. Power is delivered to it practically only from the near-by generating stations of the network.

For example, if a short circuit occurs 100 miles from a station and the voltage is sustained at 100,000 volts, 60 cycles, at the generating station, a current corresponding to only about 100,000 kv-a. will be delivered from the station. This is not such an excessive amount as to interfere with the safe opening of the circuit breakers. The presence of protective reactances very greatly reduces the short-circuit current, so that it may be said that a station 100 miles (160 km.) away from a short circuit cannot send a dangerous amount of current to the short circuit.

The greatest danger, then, comes from a short circuit in the immediate neighborhood of the largest generating station, and in that case the short-circuit current is supplied almost entirely by the nearest station. The largest circuit breakers will therefore not need to be designed with regard to the capacity of the entire network, but only of the stations in which they are located. Circuit breakers are at present in successful operation in connection with as large generating plants as are likely to be constructed and so the problem of handling short circuits will probably not impose a limitation upon the size of transmission networks.

The two systems of varying-voltage control and constant-voltage control have been described as being quite distinct. There is really, however, a middle ground between them. For instance, consider a line operated with 20 per cent voltage variation at the generators between no-load and full load, and with a steady voltage at the receiver. Now by installing a small number of synchronous motors at the receiver, the generators may be operated with only 10 per cent variation, the synchronous motors being used to hold the receiver voltage constant. Twice the number of synchronous motors would allow constant-voltage operation at both generators and receivers. It is possible, therefore, to install a small amount of machinery and obtain a proportionate improvement in closer regulation or in increased carrying capacity of the line.

The above fact is of great importance in relation to the commercial application of the principles of constant voltage operation, since a new method appears much more attractive to a transmission company if the change can be made gradually without interrupting service, and if the results of a small alteration can be observed before investing any large amount of capital.

Many power companies offer special terms to induce their customers to install synchronous motors and thus raise the power factor of the load. This can scarcely be called a step in the direction of using the principles of constant-voltage transmission, since the field current of the synchronous motors is not adjusted with a view toward regulating the line voltage. The advantages of a high power factor of load are very small indeed compared with the large advantages to be obtained from adjustable power factor.

It must not be supposed that the voltage at all points of a constant-voltage transmission line or network has exactly the same value. At all points where there are generators or synchronous motors whose field current can be adjusted, the voltage will be held steady. For the best economy, however, the generator voltage should be held at a higher value than the receiver voltage. Thus the voltage at the generating stations may be held constant at 110,000 volts, while the voltage at the receiver stations may be held steady at 90,000 volts. This involves running the synchronous motors with a weak field and a lagging power factor at no-load, and there is a limit in doing this when the motors are carrying a mechanical load, due to the

danger of the motors dropping out of step. However, the capacity of synchronous motors required is so large that most of them would have to run unloaded as synchronous condensers, since mechanical loads could be found for only a few of them. The curves which have been given assume that the synchronous condensers will operate at their full rating of lagging current at no-load, as well as with leading current at full load.

Synchronous condensers can be designed so as to remain in step, when running unloaded at 100 per cent power factor, as tenaciously as a fully-loaded induction motor. If necessary, the starting torque could be sacrificed for the sake of the synchronizing power, and the condensers could be started by small starting-motors, though it would be preferable to have them self-starting. At times of very light load on the line, such condensers can operate safely with weak fields and lagging power factor. Thus, in spite of the fact that loaded synchronous motors and synchronous converters are commonly regarded, and rightly so, as a very unstable element in transmission line operation, it may be stated that the addition of properly designed unloaded synchronous condensers to a transmission system, as described in this paper, does not decrease the reliability of the system. In fact, the extra reactance which would be used, as described above, renders the line more reliable instead of less so. It may be mentioned that probably more time would be taken in getting load on a line, after a temporary shut-down, where synchronous condensers are installed, but this is not a serious disadvantage if the system is more safe and dependable.

The charging current of the line due to the condenser effect is the same under all conditions of load, and does not affect the amount of machinery necessary for the adjustment of the line voltage as described in this paper. The effect of the charging current is to raise the voltage at the receiver, by a constant amount. The operation of a long constant-voltage line is made more satisfactory by the charging current, but the charging current cannot be considered a help when the line is operated with varying voltage.

It has been found in commercial practise with short lines that constant voltage transmission is worth while merely on account of the improvement in service. In the following paragraphs, estimated costs are given for comparatively long lines, so as to show, even more definitely than by the curves already discussed, that where a line is long, or land is high in value, it

pays to adopt constant-voltage transmission, even without considering the improvement in service.

Summary

Constant voltage transmission requires adjustable power factor.

Advantages.

1. Better service—no variation in voltage.
2. Better protection, due to high reactances.
3. Tendency to use the frequency of 60 cycles.
4. Increased carrying capacity of line. The limit is changed from maximum voltage variation to maximum energy loss. This allows more power to be transmitted or the distance to be increased, without the voltage being raised.
5. Lower total cost for long lines. The saving in cost is greatest for long lines or large networks, large quantities of power, large conductors, and for the frequency of 60 cycles.
6. The method is easy to apply to existing lines. The change can be gradual, and no change is necessary in line construction.

Disadvantages.

1. Cost and attendance of additional rotating machinery.
2. Higher total cost for short lines.
3. In order to obtain the greatest economy from constant-voltage operation, the losses must be increased, and the number of separate lines, which are useful as reserves, must be reduced.
4. Tendency of synchronous machinery to drop out of step, and delay in putting load on the line again after shut-down.

Data Pertaining to Constant Voltage Transmission

Formula for Voltage Drop from Generator to Receiver.—(Neglecting charging current.)

Let E be the voltage at the receiver.

Let I be the current, in total amperes, at a power factor $\cos\theta$ at the receiver end.

Let $P = I\cos\theta$

Let $Q = I\sin\theta$

Let R be the resistance and X the reactance, of one conductor.

COMPARISON OF THE TWO SYSTEMS FOR A 200-MILE TRANSMISSION PROJECT

	The usual varying-voltage method	Constant-voltage method
Distance	200 miles	200 miles
Power delivered	33,000 kw.	33,000 kw.
Power factor of load	90 per cent	90 per cent
Frequency	60 cycles	60 cycles
Number of three-phase circuits	3	1
Conductors, copper cable	No. 0000	350,000 cir. mil.
Maximum voltage on line	116,000	116,000
Voltage at load end	100,000	85,000
Reactive drop in transformers at each end	4 per cent	5 per cent
Reactive drop in protective coils at each end	4 per cent	7 per cent
Synchronous condensers at load end	None	18,000 kv-a.
Synchronous condensers required at no-load		16,500 kv-a.
Voltage variation	21 per cent	None
Voltage variation due to line alone	14 per cent	None
Efficiency of transmission	94 per cent	87 per cent
Power factor at generators	99 per cent lagging	89 per cent lagging
Approximate Costs.		
Towers, ground cables, insulators and erection	$1,140,000	$440,000
Copper cables, at 18 cents lb.	1,080,000	600,000
Synchronous motors and space in substations, at $10.00 per kv-a.		180,000
Cost of line, exclusive of land	$2,220,000	$1,220,000
Saving		1,000,000

N.B. The charging current of the line was allowed for in calculating the above results.

COMPARISON FOR A 100-MILE TRANSMISSION SYSTEM

	Varying-voltage method	Constant-voltage method
Distance	100 miles	100 miles
Power delivered	54,000 kw.	54,000 kw.
Power factor of load	80 per cent	80 per cent
Frequency	60 cycles	60 cycles
Number of three-phase circuits	3	1
Conductors, copper cable	250,000 cir. mil.	400,000 cir. mil.
Maximum voltage on line	113,000	113,000
Voltage at load end	100,000	90,000
Reactive drop in transformers at each end		5 per cent
Reactive drop in protective coils at each end		5 per cent.
Synchronous condensers at load end	None	42,700 kv-a.
Synchronous condensers required at no load		21,500 kv-a.
Regulation due to line alone	15 per cent	None
Efficiency of transmission	95 per cent	91 per cent
Power factor at generators	87 per cent lagging	89 per cent lagging
Approximate costs.		
Towers, ground cables, insulators and erection	$618,000	$227,000
Copper cables at 18 cents per lb.	642,000	343,000
Synchronous condensers and space in sub-stations at $10.00 per kv-a.		427,000
Cost, exclusive of land	$1,260,000	$997,000
Saving		263,000

N.B.: The charging current of the line was allowed for in calculating the above results.

Then the drop in volts for a lagging current =

$$E - \sqrt{(E + PR + QX)^2 + (PX - QR)^2}$$

$$= \text{approximately } PR + QX + \frac{(PX - QR)^2}{2\,(E + PR + QX)}$$

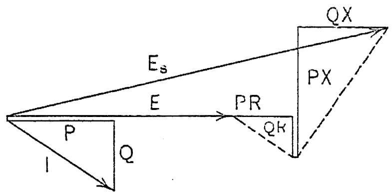
(See Fig. 6a.)

The drop in volts for a leading current is approximately

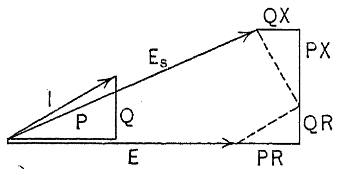
$$PR - QX + \frac{(PX + QR)^2}{2\,(E + PR - QX)}$$

(See Fig. 6b.)

The above approximate forms should not be used when the quantities $(PX - QR)$ or $(PX + QR)$ are greater than about 25 per cent of E. In such cases use the form involving the radical.



(a) LAGGING CURRENT.



(b) LEADING CURRENT.

FIG. 6

Diagram for Required Amount of Leading Current

Let the voltage be held at a steady value E at the receiver end of the line, and at a steady value E_s at the supply end of the line. Let Q be a leading current.

Then $E_s^2 = (E + PR - QX)^2 + (PX + QR)^2$

or $(P^2 + Q^2)\,(R^2 + X^2) + 2\,EPR - 2\,EQX = E_s^2 - E^2$

$$\text{That is, } P^2 + Q^2 + \frac{2\,ER}{R^2 + X^2}\,P - \frac{2\,EX}{R^2 + X^2}\,Q = \frac{E_s^2 - E^2}{R^2 + X^2}$$

the charging current being neglected.

This is the equation of a circle, when Q is plotted for different values of P.

Let the center of the circle be (a, b) and the radius c.

Then the circle is $(x - a)^2 + (y - b)^2 = c^2$

or $x^2 + y^2 - 2\,a\,x - 2\,b\,y = c^2 - a^2 - b^2$

$$\text{Therefore } a = -\frac{ER}{R^2 + X^2}$$

$$b = +\frac{E\,X}{R^2 + X^2}$$

and

$$c^2 = \frac{E_s^2 - E^2}{R^2 + X^2} + a^2 + b^2 = \frac{E_s^2}{R^2 + X^2}$$

The circle may now be drawn as in Fig. 5, which is the diagram for the 200-mile (321-km.) line described above. The current Q_s supplied by the synchronous condensers is larger than Q, since the lagging current, Q_l, of the load must be neutralized. That is,

$$Q_s = Q + Q_l$$

Q_l is plotted as a straight line, assuming that the power factor of the load remains constant.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

BY JOHN C. PARKER

The general mathematical treatment of the synchronous motor and its special application as a synchronous condenser—so-called—for the placing of a leading power factor load on a distribution system, is so thoroughly familiar and simple that the present paper will not concern itself with the features of specific analysis. It is desired to point out a few specific applications that may be made, and the means of securing co-operative effort between the central station and its customers for the purpose of securing synchronous motor load and thereby bettering service.

It may be recognized that in general the customer of a distributing company has little technical interest in the use of synchronous equipment, since it is somewhat more expensive than induction motor equipment, does not lend itself readily to extremely small unit installation, and is, even with more modern apparatus, slightly less substantial and easy to operate. On the other hand, on the larger units these difficulties are of less significance, and therefore we may look for industrial applications of synchronous motors where relatively large concentrated power applications occur, possibly supplemented by, but in general differentiated from, group and individual motor drive distributed throughout a manufacturing plant. It will, therefore, be the case that such applications must be made on large centralized equipment, such as air compressors, refrigerating machines, pumps, et cetera, rather than on individual machines, or in those places where the industry depends on one centralized power supply using mechanical distribution throughout the plant; such industries being, for example, the smaller milling

concerns, where all of the manufacturing processes are correlated, giving no diversity factor on the different machines and thereby most readily lending themselves to a mechanical power distribution, all of which operates all of the time when the mill is in commission. Such a mechanical distribution in general offers high efficiency of distribution with a not excessive first cost and maintenance, and with fairly close synchronizing of the different machines driven, so that in such a case individual induction motor installation with electric distribution of power is not economically justified.

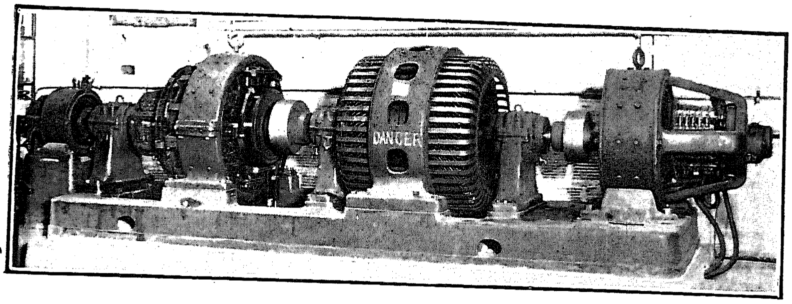
Obviously the synchronous motor in industrial use will not find its place where frequent starting and stopping are required, nor where the starting must be done under full load.

In the cases of relatively large centralized power utilization, the consumer's motive for synchronous motor application is found either in a rate schedule favorable to unity power factor or leading load, in a sharing of the expense of the initial installation by the central station company, or in a special arrangement into which the central station enters for a class rate made lower than the rate offered for induction motor service in consideration of the improvement of distribution conditions, and offered only where such an installation will prove advantageous to the central station company.

Practically all modern systems of charge for electric service are based on the maximum demand in conjunction with the kilowatt-hours, either in the form of a direct charge for power and another direct charge for energy, or on the load factor distributed over a period of time, in which case the charge comes back to either a recorded demand charge or the rating of the connected apparatus. A metered system of demand seems to be distinctly preferable.

By having such a metered demand based on the kilovolt-amperes rather than on the kilowatts, the consumer has a material interest in keeping the power factor as near to unity as possible. This is particularly the case where energy is supplied from a hydroelectric enterprise over a long distance transmission line. In such case a kilovolt-ampere basis of charge is, the writer believes, the rule, and the incentive to the customer to make synchronous installation is a matter of anywhere from ten to thirty per cent of the annual cost of power.

An additional feature, which in the writer's practise is being incorporated into industrial synchronous motor applica-



[PARKER

FIG. 1—SYNCHRONOUS MOTOR-DRIVEN BATTERY CHARGING SET

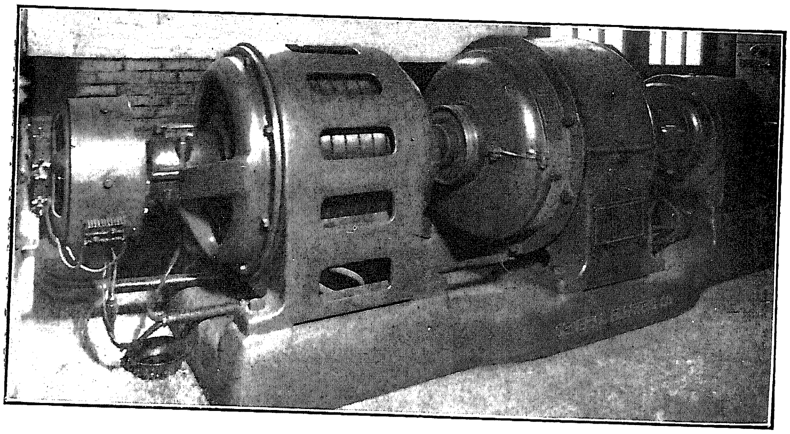


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FIG. 2—SYNCHRONOUS MOTOR—DRIVEN SET FOR REFRIGERATING MACHINE DRIVE BY VARIABLE VOLTAGE CONTROL

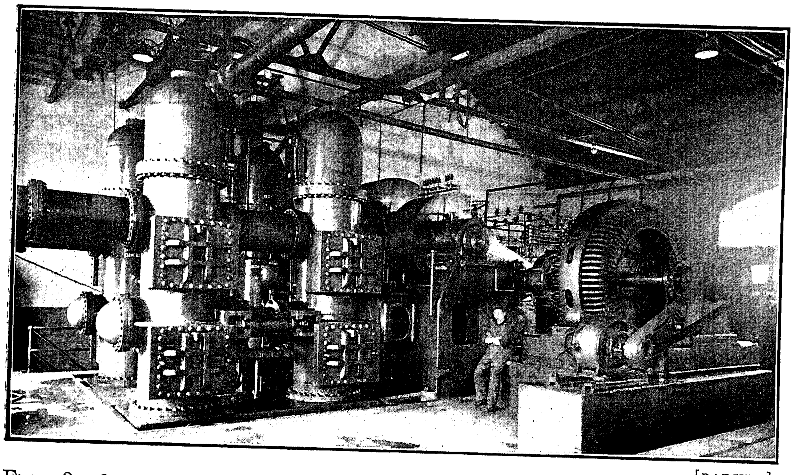

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FIG. 3—6 000,000 GALLON VARIABLE STROKE PUMP DRIVEN BY 600-H.P. SYNCHRONOUS MOTOR

tions, is the use of automatic potential regulators for holding constant voltage at distant points in the transmission line, either with or without inductance inserted in series with the line.

Where the aggregate leading quadrature kilovolt-amperes which it is practicable to get connected to the lines is less than the aggregate lagging quadrature kilovolt-amperes due to induction load, it is manifestly undesirable to insert a series inductance, since the latter would serve to reduce the power factor of the feeder load and maintain a certain minimum potential drop; but even in such a case the synchronous motor with constant potential relay is useful in supplying the leading kilovolt-amperes as the lagging kilovolt-amperes of the induction motor load increase, and vice-versa, thus at all times keeping the condition of the feeder, so far as wattless kilovolt-amperes are concerned, at least as good as the best condition obtaining prior to the installation of the synchronous equipment, and throughout the major part of the day very much better.

Where the synchronous quadrature demand can be made in excess of the lagging quadrature demand from induction motors, it then becomes desirable to put inductance in series with the feeder, thereby overcoming drop due to the in-phase amperes operating in conjunction with the line resistance.

The use of this remote potential control has certain advantages over control by station regulators. First, it combines the two functions of load carrying and of regulation in one piece of apparatus. Second, it is independent of certain approximations in regard to the feeder characteristics; and third, it is independent of the distribution of the load along the feeder at varying hours of the day.

This last factor is of very considerable importance, since a station regulator with a compensator to simulate the line impedance must be arranged for an arbitrarily assumed load distribution, while on most distribution systems in the larger cities, at least, the alternating current feeders traverse a belt of residential territory surrounding the central direct current district, and then pass into the outlying industrial district. Where one set of feeders is maintained for both the residential and industrial districts, the center of load shifts between five and six o'clock p. m. from the industrial load of the outlying districts to the lighting load of the residential districts, and therefore voltage regulator compensation which is carried for one hour of the day is inaccurate for another hour; whereas, with the synchro-

nous motor used as a potential regulator, a motor at all times endeavors to hold strictly constant voltage at the point at which the potential relay is applied to the transmission line.

In view of the fact that such potential regulating relay is only concerned with the voltage delivered to it, a series of such installations may be installed along the length of a feeder with inductances of a simple type inserted into the feeder at points so chosen between the synchronous motor service taps as to have the potential at two adjacent inductances equally high above and below the voltage for which the regulator is set, thereby getting the flattest voltage curve between these inductances and very considerably better regulation over the whole length of the line.

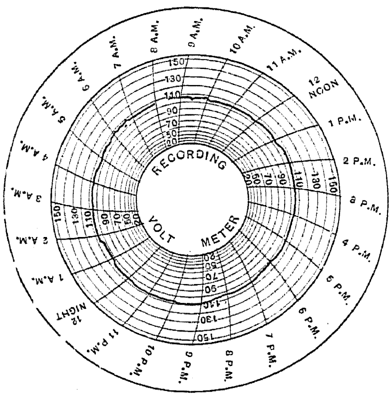


FIG. 4—VOLTAGE AT REFRIGATING PLANT. AUTOMATIC VOLTAGE REGULATOR CUT OUT. SYNCHRONOUS MOTOR OPERATING AT 75 PER CENT LAGGING POWER FACTOR

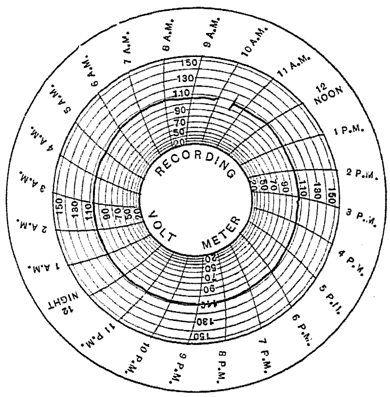


FIG. 5—SAME CIRCUIT WITH AUTOMATIC POTENTIAL REGULATOR IN OPERATION

As the voltage distribution curve along a feeder carrying uniformly distributed load of uniform character is a parabolic function of distance, it is manifest that the segmentation of voltage regulation of such series inductances reduces the variation of potential to a function which is a square of the length of the segments of the line, so that this segmental regulation with but slight multiplication of the segments makes for a material betterment in the conditions throughout the circuit.

It is perhaps hardly necessary to indicate that what we are interested in is primarily leading quadrature kilovolt-amperes, and that these can be got with less and less additional investment

and operating losses as the power factor approaches unity in a machine where power factor correction and shaft load are combined in one motor. This points to the desirability of having connected to the lines as many and as large synchronous motors as may be commercially practicable, rather than combining the power factor correction for a given circuit all in one machine of limited size, or in a synchronous motor used merely for power factor correction.

As to the applications that may be made of the synchronous motor, it may be said that the simplest application is as the driving end of a motor-generator set, where a variable direct-current voltage is desired for such purposes as battery charging in large garages, and speed control of refrigerating apparatus. The illustrations show two such sets, one of 268 kilovolt-amperes

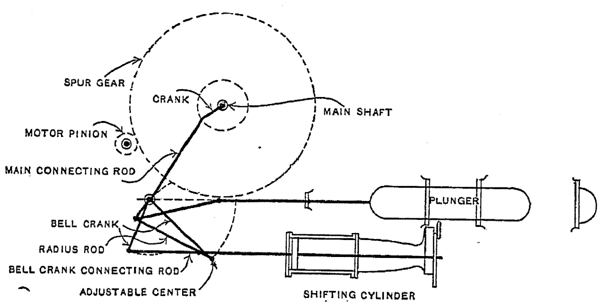


FIG. 6—LINE DIAGRAM OF 6,000,000-GALLON VARIABLE STROKE PUMP (SEE FIG. 3)

capacity at 85 per cent power factor, driving two generators, one of which is used in charging pleasure vehicles and the other for the higher voltage commercial trucks. The other illustration referred to, shows a four-unit set, consisting of a 210-kilovolt-ampere, 70 per cent leading power factor synchronous motor driving a 25-kilowatt constant voltage generator for general power purposes, a small exciter, and a 90-kilowatt direct-current generator, the field excitation of which is varied to supply variable voltage to the armature of the motor operating a refrigerating machine.

A type of application but little used is that in which the driven apparatus itself is adapted to variable output, and to synchronous motor starting. One such case is shown in the illustration of a 6,000,000-gallon pump operated by a 600-horse power, 375-volt synchronous motor. In this case the pump

stroke is made variable by means of a linkage hydraulically operated, whereby the piston stroke may be reduced quite to zero and the no-load torque thereby brought well within the pull-in torque of the motor. After the motor is in operation, the stroke of the pump may be varied at will, so as to deliver anything from zero up to 6,000,000 gallons per 24 hours. The writer is of the opinion that a great many synchronous motor applications may be found where similar adaptations of the mechanically driven apparatus to the requirements of synchronous drive may be accomplished.

As an indication of what may be looked for in this line, there has been developed an air compressor which, operating at constant rotative speed of the shaft, varies its output by air valves operated by a mechanism similar to that of a corliss engine. The corliss gear varies the cut-off on the intake, and thereby limits the work done per stroke, while the compressor may be relieved entirely of load at starting by blocking the valves open.

Another method of accomplishing the same result has been suggested by Mr. I. Lundgaard, Junior member of the American Society of Mechanical Engineers, who recommends the adaptation of constant speed motor drive to variable output for air and ammonia compressors by means of an adjustable clearance space to be secured through the use of small cylinders with stop pistons, or through a series of chambers communicating with or cut off from the clearance space by separate valves. The combination of such an arrangement with a by-pass valve obviates the necessity for variable speed and high starting torque, and through such arrangement the range of industrial application of synchronous motors is very widely extended.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

THEORY OF THE NON-ELASTIC AND ELASTIC CATENARY AS APPLIED TO TRANSMISSION LINES

C. A. PIERCE, F. J. ADAMS AND G. I. GILCHREST

Though many engineers have written articles on the subject of tensions and sags in suspended wires, few have given any attention to the theory of the subject, being satisfied to refer to some text-book, or other guide, for authority. When the novice turns to these references, he usually finds them insufficient for the understanding of the articles in which the references occur and he is forced to spend more or less time in recreating the articles. It would seem then that there is need for an article dealing with the theory of the catenary as applied to transmission lines. Furthermore, there seems to be need for more experimental data to test the accuracy of the equations with the actual measured values on real spans. It is believed that these data can be obtained in the laboratory on short spans with small wires better than would be possible out of doors on long spans with larger wires, because of the readiness with which various conditions can be controlled in the laboratory.

This article deals with the theory of the catenary as applied to transmission lines, and experimental data are compared with the values derived by use of the theoretical equations.

Theoretical

When a perfectly flexible elastic string hangs between two horizontal supports and is acted on by gravitation only, it takes the form of a curve which has been called the elastic catenary. The equation for this curve is deduced as follows:

Referring to Fig. 1, let the length of the arc of the elastic catenary, P_2OP_1. be measured from 0, the lowest point of the

arc. Consider an element, dl, of the arc between two points, P and P'. The element dl is under tension and consequently is stretched. If the unstretched length of dl is $d\sigma$, then by Hooke's law,

$$dl = d\sigma\,(1 + \lambda\, T),$$

where λ is the elastic constant of the string and T is the tension which stretches length $d\sigma$ into length dl. If the weight of unit length of the unstretched string is W, then the weight of dl, which is equal to weight of $d\sigma$, is equal to $W\,d\sigma$. Substituting the value of $d\sigma$ as given in the formula above, the weight of element dl is equal to $W\,dl \div (1 + \lambda\, T)$.

The vertical component, V, of the tension at P differs from that at P' by the weight of the element dl, hence

$$dV = W \frac{dl}{1 + \lambda\, T}$$

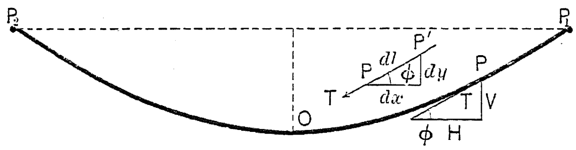


FIG. 1

But $V = H \tan\phi$, where H is the horizontal component of the tension at P and ϕ is the angle between the tension at P and the horizontal component H. Hence,

$$d\,(\,H \tan\phi) = W \frac{dl}{1 + \lambda\, T}$$

or, since H is constant along the arc,

$$d\,(\tan\phi) = \frac{W}{H}\frac{dl}{1 + \lambda\, T}$$

Letting $W \div H = 1 \div K$ and $\lambda\, H = N$, where K and N are constants, and substituting $T = H \sec\phi$,

$$\begin{aligned} dl &= K\,(1 + N \sec\phi)\, d\,(\tan\phi) \\ &= K\,(1 + N \sec\phi) \sec^2\phi\, d\phi \\ &= K \sec^2\phi\, d\phi + K\, N \sec^3\phi\, d\phi \qquad (1) \end{aligned}$$

Now,

$$\int \sec^2\phi \, d\phi = \tan\phi$$

and

$$\int \sec^3\phi \, d\phi = 1/2 \, (\sec\phi \tan\phi + gd^{-1}\phi)$$

To prove the latter equation, which is not one of the simpler integrals, one can differentiate the answer.

$$\begin{aligned} d\,[1/2\,(\sec\phi \tan\phi + gd^{-1}\phi)] \\ &= 1/2\,[\tan^2\phi \sec\phi\, d\phi + \sec^3\phi \, d\phi + \sec\phi \, d\phi] \\ &= 1/2\,[\sec^3\phi + \sec\phi\,(\tan^2\phi + 1)]\, d\phi \\ &= \sec^3\phi \, d\phi \end{aligned}$$

Hence, integrating (1)

$$l = K \tan\phi + \frac{K N}{2} (\sec\phi \tan\phi + gd^{-1}\phi) \qquad (2)$$

This equation for the length, l, of an arc of the catenary is known as the intrinsic equation of the curve because it gives the length of the arc in terms of the angle of bending, ϕ, of the arc, and constants. This equation can be changed into equations based upon the rectangular co-ordinate system. To do this let the direction $P_2 P_1$, Fig. 1, determine the direction of the X-axis and the vertical to $P_2 P_1$ determine the direction of the Y-axis, the position of the origin of the co-ordinates being as yet unknown. As seen in Fig. 1, $dy = dl \sin\phi$. But, as proved above, $dl = K\,(\sec^2\phi + N \sec^3\phi)\, d\phi$. Hence,

$$\begin{aligned} dy &= K \sin\phi\,(\sec^2\phi + N\sec^3\phi)\, d\phi \\ &= K\,(\sec\phi \tan\phi + N \sec^2\phi \tan\phi)\, d\phi \end{aligned}$$

and

$$y = K\,(\sec\phi + N/2 \tan^2\phi) \qquad (3)$$

Also, as seen in Fig. 1, $dx = dl \cos\phi$. Hence,

$$\begin{aligned} dx &= K \cos\phi\,(\sec^2\phi + N\sec^3\phi)\, d\phi \\ &= K\,(\sec\phi + N \sec^2\phi)\, d\phi \end{aligned}$$

and,

$$x = K\,(gd^{-1}\phi + N \tan\phi) \qquad (4)$$

The constants of integration for the two equations of y and x are zero if the origin of co-ordinates is chosen properly. If the Y-axis is taken so that it passes through 0, the center of the

arc of the catenary, then equation (**4**) is satisfied. And if the origin of co-ordinates is taken a distance K below the point 0, then equation (**3**) is satisfied.

It is desirable to eliminate the angle ϕ from equations (**3**) and (**4**), but this cannot be done at all easily so the equations are left in the form given above.

Collecting formulas for the elastic catenary:

$$l = K\,[\tan\phi + N/2\,(\sec\phi\tan\phi + gd^{-1}\,\phi)] \qquad (5)$$

$$y = K\,(\sec\phi + N/2\,\tan^2\phi) \qquad (6)$$

$$x = K\,(gd^{-1}\,\phi + N\tan\phi) \qquad (7)$$

$$T = H\sec\phi = K\,W\sec\phi \qquad (8)$$

$$H = T \div \sec\phi \qquad (9)$$

$$V = T\sin\phi \qquad (10)$$

$$K = \text{the } y\text{-intercept of catenary} \qquad (11)$$

Using subscripts, as l_1, etc., to refer to the value of l at one of the supports, etc.

$$L_1 = 2\,l_1 = 2\,K\,[\tan\phi_1 + N/2\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)] \qquad (12)$$

$$y_1 = K\,(\sec\phi_1 + N/2\,\tan^2\phi_1) \qquad (13)$$

$$X_1 = 2\,x_1 = 2\,K\,(gd^{-1}\,\phi_1 + N\tan\phi_1) \qquad (14)$$

$$T_1 = K\,W\sec\phi_1 \qquad (15)$$

$$H = \text{Const.} = T_1 \div \sec\phi_1 \qquad (16)$$

$$V_1 = T_1\sin\phi_1 \qquad (17)$$

$$S_1 = y_1 - K = K\,(\sec\phi_1 - 1 + N/2\,\tan^2\phi_1) \qquad (18)$$

where L_1 is the length of arc between supports, *i.e.*, the length of the stretched string, y_1 is the Y-coordinate of a support, X_1 is the length of span, T_1 is the tension tangential to the string at either support, S_1 is the sag at the center of the span and is equal to the vertical distance from 0 to the line between the supports, etc.

The equations for length of arc, span, tension, sag, etc., are in terms of K, N, and functions of ϕ_1. As these equations are difficult to use, it is customary to assume for a first approximation that N is equal to zero, *i.e.*, that the string does not stretch appreciable under tension. Making this approximation, the equations of the simple catenary are deduced. They are:

$$L_1 = 2\,K \tan \phi_1 \tag{19}$$

$$y_1 = K \sec \phi_1 \tag{20}$$

$$X_1 = 2\,K\, gd^{-1}\, \phi_1 \tag{21}$$

$$T_1 = K\, W \sec \phi_1 \tag{22}$$

$$H = T_1 \div \sec \phi_1 \tag{23}$$

$$V_1 = T_1 \sin \phi_1 \tag{24}$$

$$S_1 = K\,(\sec \phi_1 - 1) \tag{25}$$

While the equations of the simple catenary can be changed into many different forms, the ones above are the simplest in form and show that the various quantities of interest to engineers in designing the mechanical characteristics of transmission lines are functions of K and ϕ_1, the tension including another factor, W, the weight of the unstretched conductor per unit length.

Unfortunately, the factor K is difficult to deal with directly. It can be eliminated in two ways; the most obvious way is to take ratios of the quantities, such as $L_1 \div X_1$, $X_1 \div T_1$, etc. The important equations below are obtained in this manner. These equations may be appropriately called *the characteristic ratios of the simple catenary.**

The characteristic ratios of the simple catenary are:

$$\frac{L_1}{X_1} = \frac{\tan\ \phi_1}{gd^{-1}\,\phi_1} \tag{26}$$

$$\frac{X_1}{T_1} = \frac{2\, gd^{-1}\ \phi_1}{\sec\ \phi_1} \times \frac{1}{W} \tag{27}$$

$$\frac{S_1}{X_1} = \frac{\sec\ \phi_1\ -\ 1}{2\, gd^{-1}\,\phi_1} \tag{28}$$

$$\frac{S_1}{T_1} = \frac{\sec\ \phi_1\ -\ 1}{\sec\ \phi_1} \times \frac{1}{W} \tag{29}$$

$$\frac{S_1}{L_1} = \frac{\sec \phi_1\ -\ 1}{2\ \tan\ \phi_1} \tag{30}$$

$$\frac{L_1}{T_1} = \frac{2\ \tan\ \phi_1}{\sec\ \phi_1} \times \frac{1}{W} \tag{31}$$

*The equations are given for one point, the support, on the catenary, because the quantities in these equations are of especial interest to engineers. The general characteristic ratios of the simple catenary are derived from the equations of l, y, x, T, etc., above.

Table I gives the numerical values of these ratios for various values of the angle ϕ_1. From these values, curves can be plotted from which the values of the ratios for any angle less than 60 deg. can be interpolated. For accurate work the curves must be plotted to a reasonable scale. However, the values in

TABLE I

THEORETICAL CHARACTERISTIC RATIOS

(Based on W, weight per unit length, equal to unity.)

Angle ϕ_1	$\frac{L_1}{X_1}$	$\frac{X_1}{T_1}$	$\frac{S_1}{X_1}$	$\frac{S_1}{T_1}$	$\frac{S_1}{L_1}$	$\frac{L_1}{T_1}$
0						
1	1.00005	0.0349	0.00436	0.000152	0.00436	0.0349
2	1.00020	0.0698	0.00873	0.000609	0.00873	0.0698
3	1.00046	0.1046	0.01309	0.001370	0.01309	0.1047
4	1.00081	0.1394	0.01747	0.002436	0.01746	0.1395
5	1.00127	0.1741	0.02186	0.003805	0.02183	0.1743
6	1.00184	0.2087	0.02626	0.005478	0.02620	0.2091
7	1.00250	0.2431	0.03066	0.007454	0.03058	0.2437
8	1.00327	0.2774	0.03508	0.009732	0.03496	0.2783
9	1.00415	0.3116	0.03951	0.01231	0.03935	0.3129
10	1.00514	0.3455	0.04397	0.01519	0.04374	0.3473
12	1.00744	0.413	0.0529	0.02185	0.0525	0.416
14	1.01084	0.479	0.0620	0.02970	0.0614	0.484
15	1.01173	0.512	0.0666	0.03407	0.0658	0.518
16	1.01340	0.544	0.0712	0.03874	0.0703	0.551
18	1.01710	0.608	0.0805	0.04894	0.0792	0.618
20	1.02130	0.670	0.0900	0.0603	0.0882	0.684
25	1.03423	0.817	0.1146	0.0937	0.1108	0.845
30	1.0510	0.951	0.1408	0.1340	0.1340	1.000
35	1.0726	1.070	0.1691	0.1808	0.1576	1.147
40	1.0999	1.169	0.2001	0.2339	0.1820	1.285
45	1.1346	1.246	0.2350	0.2929	0.2071	1.414
50	1.1792	1.299	0.2749	0.3571	0.2331	1.532
55	1.2373	1.324	0.3220	0.4264	0.2603	1.638
60	1.3152	1.317	0.3796	0.5000	0.2887	1.732

Table I are computed for values of the angle, ϕ_1, sufficiently close together so that values may be interpolated from the table directly for all ordinary work without resorting to curves. The constant, W, is assumed to be unity in Table I. The values of the ratios for any weight per unit length of conductor is obtained by simple multiplication, using the reciprocal of W as

indicated in equations (**26**) to (**31**) inclusive. Any problem in connection with the simple catenary, in which any two of the quantities occurring in the characteristic ratios are given, can be solved by means of Table I. Thus, if length of conductor and span are given, the tension, sag, etc., can be obtained immediately from the table.

The other method of eliminating K from equations (**19**) to (**25**) inclusive is not quite so obvious as the first method. Since some of the equations below are of interest in their general form, *i.e.*, when they are not referred to the point of suspension, K will be eliminated from equations (**5**), (**6**), (**7**), etc. Letting N equal zero in equations (**6**) and (**7**),

$$y = K \sec \phi$$
$$x = K\, gd^{-1}\, \phi$$

Combining and remembering that $dy \div dx = \tan \phi$

$$y = K \sec gd \frac{x}{K} = K \cosh \frac{x}{K} \tag{32}$$

$$\frac{dy}{dx} = \sinh \frac{x}{K} = \tan \phi \tag{33}$$

$$\phi = \tan^{-1} \sinh \frac{x}{K} \tag{34}$$

From (**5**), letting N equal zero and substituting (**34**),

$$l = K \tan \phi = K \sinh \frac{x}{K} \tag{35}$$

$$L_1 = 2\, l_1 = 2\, K \sinh \frac{x_1}{K} = 2\, K \sinh \frac{X_1}{2\, K} \tag{36}$$

From (**8**) and (**6**), letting N equal zero and combining,

$$T = K\, W \sec \phi$$
$$y = K \sec \phi$$
$$T = W\, y \tag{37}$$

Substituting (**32**) in (**37**),

$$T = W\, K \cosh \frac{x}{K}$$

$$T_1 = W\, K \cosh \frac{x_1}{K} = W\, K \cosh \frac{X_1}{2\, K} \tag{38}$$

Combining (**36**) and (**38**),

$$\frac{L_1}{T_1} = \frac{2}{W} \tanh \frac{x_1}{K}$$

$$K = \frac{x_1}{\tanh^{-1} \frac{W L_1}{2 T_1}} = \frac{X_1}{2 \tanh^{-1} \frac{W L_1}{2 T_1}}$$

Substituting this value of K in (**38**), letting $L_1 \div 2 T_1 = Q_1$,

$$T_1 = \frac{W X_1}{2 \tanh^{-1} \frac{W L_1}{2 T_1}} \cosh \tanh^{-1} \frac{W L_1}{2 T_1}$$

$$= \frac{W X_1}{2 \tanh^{-1} W Q_1} \times \frac{1}{\sqrt{1 - W^2 Q_1^2}} \qquad (\mathbf{39})$$

The proof of the reduction formula for cosh $\tanh^{-1} x$ is in every way analogous to the proof of the reduction formula for cos $\tan^{-1} x$.

By proofs similar to the one leading to (**39**)

$$L_1 = \frac{X_1}{\tanh^{-1} W Q_1} \times \frac{W Q_1}{\sqrt{1 - W^2 Q_1^2}} \qquad (\mathbf{40})$$

$$S_1 = \frac{X_1}{2 \tanh^{-1} W Q_1} \left(\frac{1}{1 - W^2 Q_1^2} - 1 \right) \qquad (\mathbf{41})$$

These last three equations give T_1, L_1, and S_1 in terms of span, X_1, weight per unit length unstretched conductor, W, and a ratio, Q_1, which is of course merely a number. Inspection of equations (**26**) to (**31**) will show that T_1, L_1 and S_1 are dependent on W only as a multiplying factor or not at all, hence in equations (**39**), (**40**) and (**41**), W can be placed equal to unity. Also X_1 can be placed equal to unity, and equations (**39**), (**40**) and (**41**) will be reduced to equations for unit span and unit weight of conductor per unit length. Since X_1 and W are only multiplying values, the tension, length of arc and sag for any values of X_1 and W are found from the values for unit span etc., by direct proportion as indicated in equations (**25**) to (**31**) and (**39**) to (**41**).

The equations (**39**) to (**41**) may be used to compute values of T_1, L_1 and S_1 with which the characteristic ratios of a simple catenary may be computed. Also, curves can be plotted between T_1, L_1 and S_1 as has already been done in an excellent article by

Mr. Thomas. Mr. Thomas did not mention in his article the method by which he obtained his values, but the equations (**39**) to (**41**) can be used for this purpose. Given suitable tables of the hyperbolic functions, these equations are simple to use, because of the presence of the same functions in all of the equations.

Example. To find the tension at point of suspension and the sag if a conductor 1001.27 ft., (305.19 m.), long is hung between two horizontal supports 1000 ft., (304.80 m.), apart, $W = 1$ lb., (0.4536 kg.). From the data given, $L_1 \div X_1 = 1.00127$. From Table I this is seen to give an angle at the supports equal to 5 deg. Hence, as read from the table, $X_1 \div T_1 = 0.1741$ or $T_1 =$ 5744 lb., (2605.4 kg.). Also, from the table, $S_1 \div X_1 = 0.02186$, or $S_1 = 21.86$ ft., (6.66 m.). These results can be checked by means of equations (**39**) to (**41**). From the values just determined, the ratio $Q_1 = L_1 \div 2\,T_1 = 0.08716$. Substituting in equation (**39**), $T_1 = 5744$ lb., (2605.4 kg.). Substituting in equation (**41**), $S_1 = 21.86$ ft., (6.66 m.), and substituting in equation (**40**), $L_1 = 1001.29$ ft., (305.19 m.). This checks the problem and also the formulas.

The above check was made using six-place logarithm tables and the Smithsonian tables of hyperbolic functions. The check is seen to be very good. When computing the values in Table I, it was found that the Smithsonian tables did not give the values of the anti-gudermanian to sufficient decimal places to allow one to determine the ratio $L_1 \div X_1 = \tan \phi_1 \div gd^{-1}\,\phi_1$ accurately for small values of ϕ_1. It will be noticed, by reference to the table, that this ratio does not differ from unity by as much as 0.1 per cent until ϕ_1 becomes as great as five degrees. Furthermore, both $\tan \phi_1$ and $gd^{-1}\,\phi_1$ are nearly equal for small values of ϕ_1. Hence, in order to calculate this ratio accurately, it was found necessary to calculate the values of $gd^{-1}\,\phi_1$ by the equation,

$$gd^{-1}\phi_1 = \log_\epsilon \tan (\pi/4 + \phi_1/2)$$

The characteristic ratios of the simple catenary, the example above, and equations (**39**) to (**41**) are all based on the assumption that the conductor does not stretch, *i.e.*, that the elastic constant, $\lambda = N \div H$, is equal to zero. If this assumption is not made, then one must use equations (**12**) to (**18**) inclusive in connection with a problem, or else make corrections in the simple formulae based on $\lambda = 0$. The constant K can be eliminated from equations (**12**) to (**18**) by taking ratios as has already been done for the equations for the simple catenary. If this is done, the six

characteristic ratios for an elastic catenary are obtained. Using bracketed quantities when they are based on the assumption of an elastic constant different from zero, the characteristic ratios follow:

$$\left[\frac{L_1}{X_1}\right] = \frac{\tan\phi_1 + N/2\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)}{gd^{-1}\,\phi_1 + N\tan\phi_1} \tag{42}$$

$$\left[\frac{X_1}{T_1}\right] = \frac{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1}{\sec\phi_1} \times \frac{1}{W} \tag{43}$$

$$\left[\frac{S_1}{X_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1} \tag{44}$$

$$\left[\frac{S_1}{T_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{\sec\phi_1} \times \frac{1}{W} \tag{45}$$

$$\left[\frac{S_1}{L_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{2\tan\phi_1 + N\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)} \tag{46}$$

$$\left[\frac{L_1}{T_1}\right] = \frac{2\tan\phi_1 + N\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)}{\sec\phi_1} \times \frac{1}{W} \tag{47}$$

Letting $N = O$, these equations reduce to equations (**26**) to (**31**) inclusive, the six characteristic ratios for the simple catenary.

It is, in general, impossible to use the characteristic ratios for the elastic catenary. Inspection of equations (**43**), (**45**) and (**47**) will show, however, that these three equations can be expressed in terms of the ratios of the simple catenary. Consider equation (**43**),

$$\left[\frac{X_1}{T_1}\right] = \frac{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1}{\sec\phi_1} \times \frac{1}{W}$$

$$= \frac{2\,gd^{-1}\,\phi_1}{\sec\phi_1} \times \frac{1}{W} + N\frac{2\tan\phi_1}{\sec\phi_1} \times \frac{1}{W}$$

$$= \frac{X_1}{T_1} + N\frac{L_1}{T_1} \tag{48}$$

$$= \frac{X_1}{T_1} + \frac{L_1}{T_1}\,\lambda\,T_1\cos\phi_1\ (\text{approx.})$$

$$= \frac{X_1}{T_1} + \lambda\,L_1\cos\phi_1\ (\text{approx.}) \tag{49}$$

From formulas (**45**) and (**47**),

$$\left[\frac{S_1}{T_1}\right] = \frac{S_1}{T_1} + \frac{\lambda}{4} L_1 \sin \phi_1 \text{ (approx.)} \tag{50}$$

$$\left[\frac{L_1}{T_1}\right] = \frac{L_1}{T_1} + \frac{\lambda}{W} T_1 \sin \phi_1 + \frac{\lambda}{2} X_1 \cos \phi_1 \text{ (approx.)} \tag{51}$$

These formulas show that the characteristic ratios for the elastic catenary can be expressed in terms of the corresponding ratios for the simple catenary together with a correction factor. Inspection will show that any correction factor is but a small fraction of the whole expression, hence the approximation is close. A problem will illustrate this point.

Let $X_1 = 1000$, $W = 1$, $\lambda = 2.41 \times 10^{-7}$, to determine the tension, sag and length of conductor when the wire is strung between horizontal supports so that $\phi_1 = 5$ deg. From Table I,

$$\frac{L_1}{X_1} = 1.00127, \text{ hence } L_1 = 1001.3$$

$$\frac{X_1}{T_1} = 0.1741, \quad \text{“} \quad T_1 = 5744$$

$$\frac{S_1}{X_1} = 0.02186, \quad \text{“} \quad S_1 = 21.86$$

Using formulas (**49**), (**50**) and (**51**),

$$\left[\frac{X_1}{T_1}\right] = 0.1743, \quad \text{hence } [T_1] = 5737$$

$$\left[\frac{S_1}{T_1}\right] = 0.003810, \quad \text{“} \quad [S_1] = 21.86$$

$$\left[\frac{L_1}{T_1}\right] = 0.1745 \quad \text{“} \quad [L_1] = 1001$$

This problem shows that if a conductor is suspended between horizontal supports 1000 units apart so that the angle ϕ_1 is equal to five degrees, the sag and tension will be essentially the same

whether one assumes the elastic constant equal to zero or equal to its true value. Inspection of equations (**48**) to (**51**) will show that this conclusion is approximately true for all sags, tensions, spans, etc.

It is to be noticed that equations (**48**), (**50**) and (**51**) are sufficient to determine the remaining three characteristic ratios of the elastic catenary.

The problem of finding how the sag and tension, etc., vary with temperature change is simple if the elastic constant is assumed equal to zero. The problem is solved at one temperature by means of Table I, using the values of L_1, W, etc., at this temperature. Then the new length and new weight per unit length are determined at the new temperature by means of the usual formulas,

$$L'_1 = L_1 \left(\frac{1 + \alpha\, t'}{1 + \alpha\, t}\right)$$

$$W' = W \left(\frac{1 + \alpha\, t}{1 + \alpha\, t'}\right)$$

where L_1 and W refer to temperature t, L'_1 and W' refer to temperature t' and α is the temperature coefficient of expansion. These new values of length and weight are substituted in the characteristic ratios for the simple catenary and the problem solved by use of Table I, assuming the span, X_1, to remain unchanged.

In all of the problems and equations above, W stands for the weight of unstretched conductor per unit length. This value includes not only the weight of the material of the conductor but also the weight of ice that may surround the conductor. If wind pressure is assumed to blow the conductor out of the vertical plane so that it still hangs in the form of a catenary curve then W will include the factor of wind pressure, the resultant weight per unit length of unstretched conductor being the vector sum of the weight of conductor, weight of ice and equivalent weight of wind pressure. It is evident that the first two factors add arithmetically and act downward in the direction of the force of gravity while the equivalent weight of wind pressure will in general be at right angles to the plane of the conductor when it hangs in its normal position, the resultant weight, W, acting in the plane in which the conductor actually hangs.

The problem of finding the change in sag, tension, etc., due to a change in W is difficult to treat accurately. The authors know of no better procedures than the approximate ones suggested by several writers, including Mr. H. W. Buck and Mr. P. H. Thomas; references to these articles are given below. This general problem could be solved immediately by use of the characteristic ratios of an elastic catenary, equations (**42**) to (**47**) inclusive, if it were not that these equations are too complex to use.

Experimental

In order to check the theoretical equations derived above with experimental data, an experimental span was erected in the laboratory. A large I-beam which ran the length of the laboratory, about 200 ft. (61.0 m.), was used as a support for the wire span. The length of the actual span was 190.70 ft. (58.12 m.). No. 4 A.w.g. hard drawn copper wire was chosen for the first tests, which are the only tests included in this article. In order to straighten the wire it was stretched to about its elastic limit and then allowed to hang several days before the measurements were begun. Each end of the wire was caught in a clamp which was free to turn in a vertical plane determined by the wire. At one end of the span, the clamp was supported by means of a system of links in such manner that the horizontal tension could be computed directly from the readings of a small platform balance. The vertical tension was taken as the weight of half of the wire included between the clamps. The sags at different points in the span were measured by a rod from stations which had been leveled by means of a surveyor's level. The sags were measured at nine equidistant stations between the points of suspension. These stations were numbered 1 to 9 consecutively, making station 5 come at the center of the span. The points of suspension were at stations 0 and 10. A gallery in the laboratory furnished the support for the stations and the wire hung down in front of this gallery. This arrangement allowed the sag measurements to be made with a much shorter rod than would have been necessary if the sags had been measured directly from the line of the suspensions. The rod with which the sags were measured ran through a guide which was set up vertically at each station, and contact with the wire was judged by means of an electrical contact arrangement. With this device no difficulty was experienced in measuring sags to about 0.02 inch (0.051 cm.), though the small vibrations of the wire caused by machinery in

the laboratory made some measurements vary by as much as 0.06 inch (0.152 cm.).

All weights were obtained on the same platform balance so that the calibration of the balance was unnecessary. It was assumed that the balance, a new one, would give a straight line for the calibration curve. All lengths were referred to either a B. & S. steel tape or to a Starrett steel tape. These tapes were accepted as accurate.

TABLE II

CHARACTERISTIC RATIOS

Comparison of Experiment and Theory

Run		$\frac{L_1}{X_1}$	$\frac{X_1}{T_1}$	$\frac{S_1}{X_1} \times 10^{-2}$	$\frac{S_1}{T_1} \times 10^{-1}$	$\frac{S_1}{L_1} \times 10^{-2}$	$\frac{L_1}{T_1}$	
No. 1	A	1.022	5.48	9.12	5.01	8.93	5.61	Exp.
"	B	1.022	5.42	9.21	5.01	9.01	5.54	theory
"	C	1.022	5.39	9.12	4.91	8.92	5.49	"
"	D	1.023	5.48	9.35	5.16	9.14	5.62	"
No. 2	A	1.011	3.95	6.32	2.49	6.25	3.99	Exp.
"	B	1.011	3.91	6.38	2.49	6.31	3.95	theory
"	C	1.011	3.88	6.32	2.45	6.25	3.92	"
"	D	1.011	3.95	6.45	2.55	6.38	3.99	"
No. 3	A	1.005	2.72	4.26	1.161	4.24	2.73	Exp.
"	B	1.005	2.69	4.31	1.161	4.29	2.70	theory
"	C	1.005	2.66	4.26	1.138	4.24	2.68	"
"	D	1.005	2.72	4.36	1.189	4.34	2.74	"
No. 4	A	1.002	1.609	2.45	0.395	2.45	1.612	Exp.
"	B	1.002	1.574	2.49	0.395	2.49	1.576	theory
"	C	1.002	1.551	2.45	0.384	2.45	1.553	"
"	D	1.002	1.611	2.55	0.412	2.55	1.612	"
No. 5	A	1.003	0.845	1.32	0.112	1.32	0.845	Exp.
"	B	1.005	0.840	1.32	0.112	1.32	0.840	theory
"	C	1.005	0.838	1.32	0.112	1.32	0.839	"
"	D	1.005	0.844	1.33	0.113	1.33	0.845	"

Each run in the tests consisted in drawing the wire up to some desired sag. Then balance readings were taken to determine the horizontal tension, and sags were measured from the leveled stations. From the former measurements the tension at the suspension could be immediately computed, using the half weight of the wire in the span as the vertical tension. The weight of the wire in the span was determined by weighing and measuring the total wire used, and at each run the wire that extended be-

yond the clamps was deducted. The angle, ϕ_1, between the tension in the wire and the horizontal could be determined from the balance readings and weight of wire. From the sag measurements the actual sags below the horizontal line through the points of suspension could be computed.

Using the measured values of ϕ_1, X_1, L_1, T_1 and S_1, the characteristic ratios for the span could be computed directly. These values are shown in Table II, lines A. Using the measured values of ϕ_1, the theoretical values of the characteristic ratios for a simple catenary are shown in lines D. Using the measured

TABLE III

SAGS (unit = ft.)

Comparison of Experiment and Theory

Stations

Run		0 and 10	1 and 9	2 and 8	3 and 7	4 and 6	5	
No. 1	A	0	6.31	11.18	14.63	16.72	17.38	Exp.
"	B	0	6.29	11.16	14.62	16.69	17.38	theory
"	C	0	6.45	11.43	14.97	17.09	17.79	"
No. 2	A	0	4.37	7.73	10.14	11.59	12.05	Exp.
"	B	0	4.35	7.73	10.13	11.57	12.05	theory
"	C	0	4.44	7.86	10.34	11.81	12.30	"
No. 3	A	0	2.95	5.23	6.85	7.82	8.13	Exp.
"	B	0	2.92	5.21	6.83	7.81	8.13	theory
"	C	0	3.00	5.33	6.99	7.99	8.32	"
No. 4	A	0	1.72	3.02	3.95	4.51	4.68	Exp.
"	B	0	1.69	3.00	3.93	4.50	4.68	theory
"	C	0	1.75	3.11	4.08	4.67	4.86	"
No. 5	A	0	0.91	1.61	2.11	2.42	2.52	Exp.
"	B	0	0.91	1.61	2.12	2.42	2.52	theory
"	C	0	0.92	1.63	2.13	2.44	2.54	"

values of S_1 and T_1, the angle ϕ_1 can be interpolated from Table I and the remaining theoretical characteristic ratios for the simple catenary can also be interpolated from Table I. These results are shown in lines B, Table II. The lines C give theoretical values based on the measured values of S_1 and X_1.

Table III, lines A, shows the measured sags at the various stations. Since the sags at stations 0 and 10, 1 and 9, 2 and 8, etc., should correspond respectively, the averages of these values are shown in the table. The theoretical sags of a simple catenary which would pass through the points of suspension and the point

of maximum sag as determined experimentally are given in lines *B*, Table III. The theoretical sags of a simple catenary making an angle, ϕ_1, at the suspension, equal to the experimental angle, are given in lines *C*, Table III.

The data could have been worked up in various ways and various comparisons made, but the tables shown above give as comprehensive an idea of the results as is possible in the space used.

Conclusion

Inspection of Table II will show that the check between experiment and theory, which is based on the characteristic ratios of the simple catenary, is very good, if the number of variable quantities is considered. Inspection of Table III will show that the theoretical sag is greater then the actual measured sag. The wire hung approximately in the form of a simple catenary, however, as is shown in the same table. In run 4, Table III, the wire seems to have departed from the catenary form at stations 1 and 9, also at 2 and 8. This seeming departure from the form of the simple catenary was due to the clamp at one end of the span becoming wedged against a bolt head as the sag was diminished. The effect is noticeable in run 3. Before making run 5, the trouble was located and the wire again hangs in the form of a simple catenary as nearly as the measurements will show.

The authors are not prepared to explain why the measured sags were less than the sags computed from the measured angle ϕ_1. If the angle ϕ_1, as measured, was too large, this would mean that the measured horizontal tension or the measured vertical tension was not accurate, but careful check of the apparatus did not prove this assumption. It should be pointed out, furthermore, that no attempt was made to correct for temperature changes of the laboratory during the experiments. The changes were small. When tested at several different times, the temperature was found not to vary more than two deg. cent.

Further experiments with wires of different sizes are being carried on at the present time. Next winter, it is proposed to test the change of sag and tension with temperature change. The apparatus was not completed in time to take advantage of the cold weather during the past winter to obtain the lower temperatures.

The authors wish to add that the use of hyperbolic functions has become too general in engineering to need apology. The use

of the Gudermannian function and its inverse are not so general, but their value is evident. The significance of these functions is partially deducible from the equations, $gd\, x = \tan^{-1}(\sinh x)$, $gd^{-1} x = \sinh^{-1}(\tan x)$. For further information about hyperbolic functions and the Gudermannian, see references.

References

Hyperbolic Functions, Professor James McMahon.

Sag Calculations for Suspended Wires. Percy H. Thomas. TRANS. A. I. E. E., Vol. XXX, p. 2229, 1911.

The Use of Aluminum as an Electrical Conductor, H. W. Buck. *Trans. Int. Elect. Congress*, St. Louis, 1904, Vol. 2, p.313.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

ELECTRICAL REQUIREMENTS OF CERTAIN MACHINES IN THE RUBBER INDUSTRY

BY C. A. KELSEY

This paper is intended to outline briefly the power requirements of some of the principal machines which work up crude rubber and render it suitable for the manufacture of various articles.

The principal source of rubber is the wild trees of Brazil, although cultivated rubber in increasing quantities is now produced in East India, Ceylon, Malayan Peninsula and Southern Mexico. The former reaches the factory in the form of balls or biscuits about a foot in diameter. Cultivated rubber is universally washed and sheeted at the plantation and is shipped in the form of cakes of folded sheets.

Washing. After the biscuits have been cut into chunks and softened in a bath of warm water, they are fed into a cracker or rough washing mill. This mill consists of two or three rolls between which the rubber passes, is torn apart and rolled out into a rough sheet. Water flowing through the rubber in its passage through the rolls washes out part of the entrapped dirt.

These mills run at a constant speed of 20 to 25 rev. per min. The load is very irregular and depends upon the feeding of the mill. A three-roll washer with continuous feeding requires an average of 25 to 35 h.p., with power peaks of 100 h.p.

The rough sheet is then passed through a single set of rolls where it is further washed and rolled out into a sheet or "crepe."

These mills run at a constant speed of about 25 rev. per min. The load is fairly uniform as the rubber is already in the form of a rough sheet. The power required averages 20 to 25 h.p. and

occasionally runs up to 50 h.p. when the sheet is introduced between the rolls after being doubled.

After the crepe has been dried either in a drying room, where it is suspended from the ceiling, or placed in a vacuum drier, it is ready to be masticated and mixed with the suitable ingredients to form various compounds.

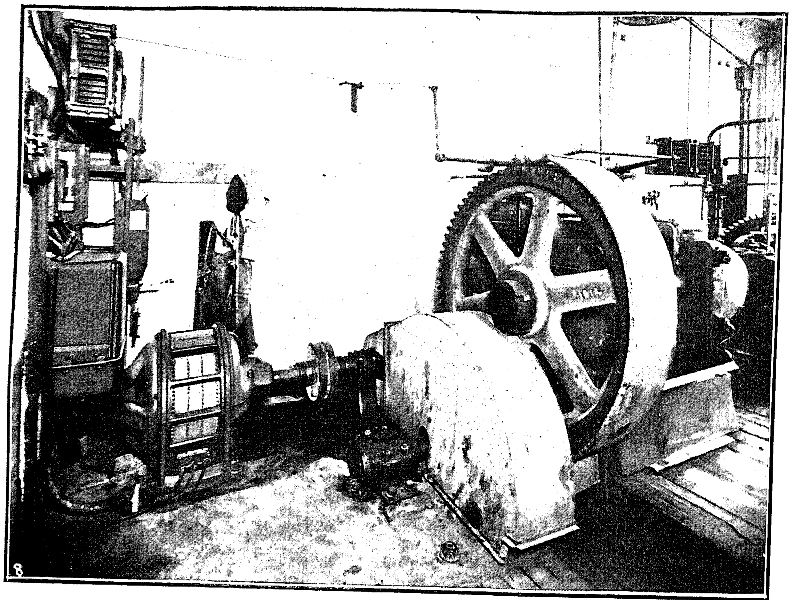
Masticating. The dried crepe must be worked or masticated into a homogeneous and plastic state before the ingredients are added. This is most economically done in a shorter mill than a mixing mill. The power required at the beginning of the process is greater than at the end and runs up to a high value as the rubber is cut free from the roll and doubled back in again. From tests on a 50-in. (1.27-m.) face mill the average power was 37 h.p. and the maximum 74 h.p., while a 60-in. (1.52-m.) face mill required an average power of 90 h.p. and a maximum of 140 h.p.

Mixing. Pure rubber is never used in the manufacture of rubber articles without first adding to it some other substance. Different materials are employed, depending upon the use and desired characteristics of the rubber product. Some materials increase the elasticity, some impart hardness and toughness and some act as mechanical fillers to cheapen the product without materially affecting the desired characteristics.

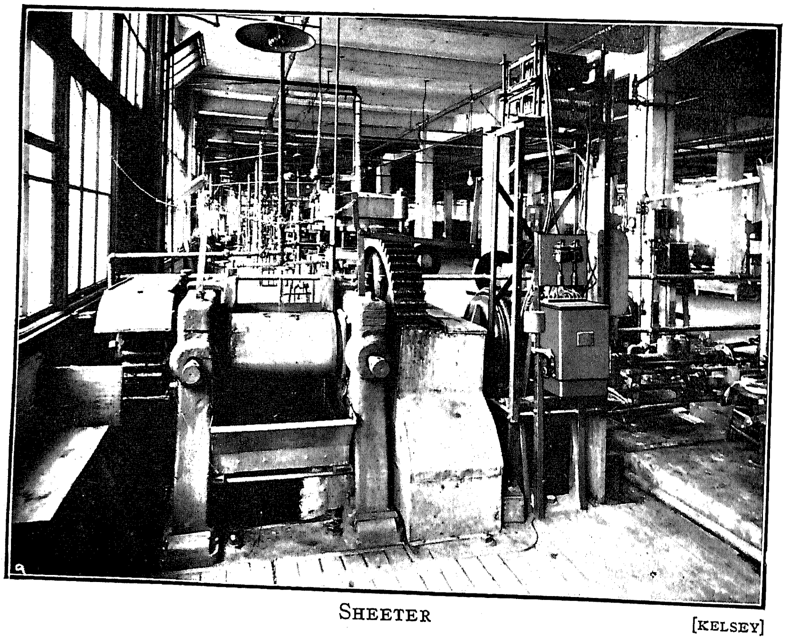
Where the rubber is masticated in the mixing mill, the predetermined weights of the various substances are added in a powdered or liquid state only after the masticated rubber has been thoroughly worked and warmed. As the ingredients impart different degrees of hardness and toughness to the final product so will the power to drive the mill vary.

The speed of the rolls ranges from 20 to 25 rev. per min. A 40-in. (1-m.) face mill requires about 20 h.p. average and 40 h.p. maximum on relatively soft compound and 25 h.p. average and 55 h.p. maximum on hard compound while a 60-in. (1.5-m.) face mill requires 55 h.p. average and 120 h.p. maximum on medium compound.

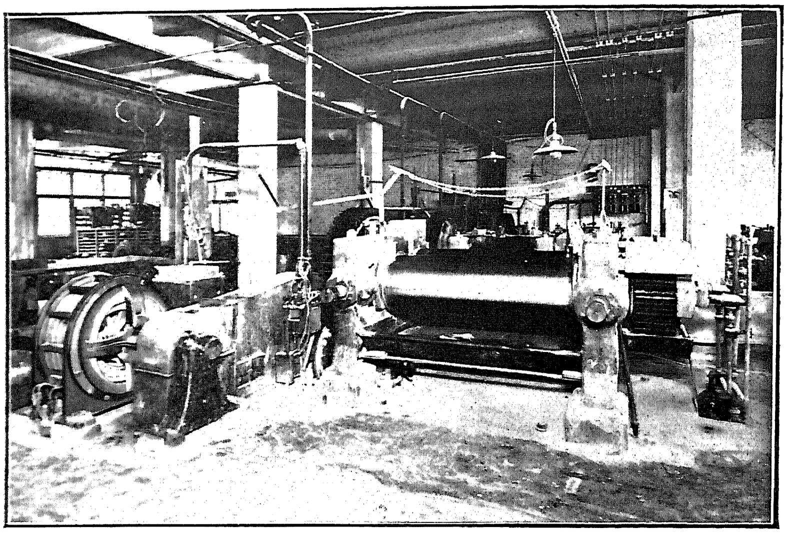
Refining. In some installations the compound after leaving the mixing mill is passed through machines that strain it and reduce it to a very thin sheet. The strainers are in principle like a meat grinder. A feed screw revolving inside a water-jacketed cylinder forces the compound through a fine mesh screen which is backed up by a perforated plate. This removes all solid foreign objects which ordinarily find their way into the



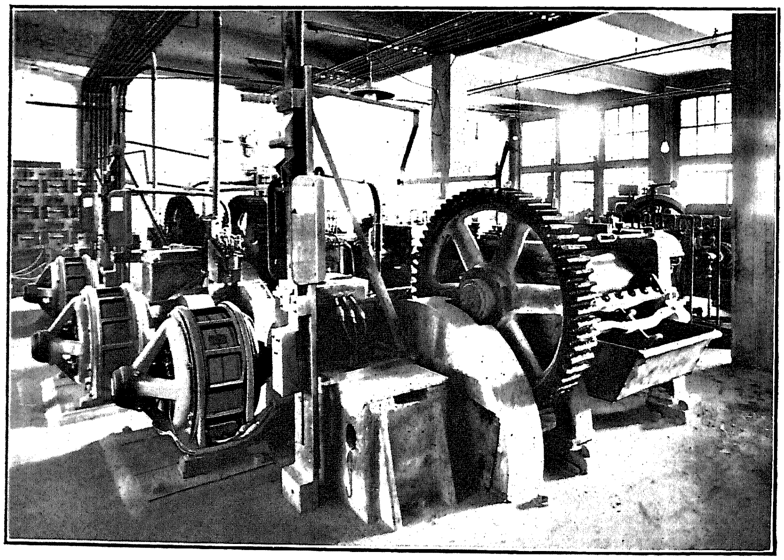
THREE ROLL WASHER [KELSEY]



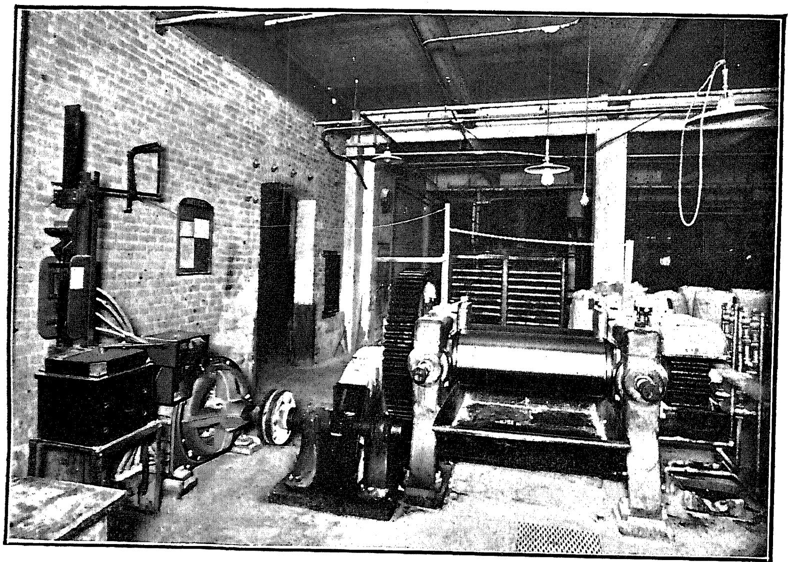
SHEETER [KELSEY]



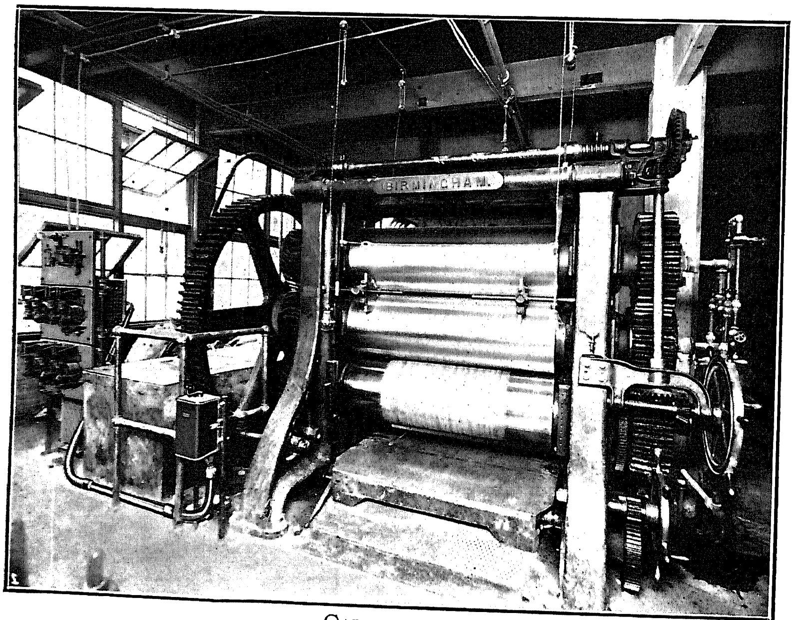
MIXING MILL [KELSEY]



REFINING MILL [KELSEY]



Warming Mill [KELSEY]



Calender [KELSEY]

ıaterial. The compound becomes heated more or less as it asses through the strainer and the final temperature must be ept below a given value. The heating varies with the compound ıd the initial temperature. An efficient means of maintaining aximum output is to vary the speed. This therefore requires an ljustable-speed motor. A two-to-one speed range is sufficient. he power required is 25 h.p. over the whole range. The harder mpounds, requiring high torque are run at the slow speeds and e soft compounds requiring less torque are run at the high eeds.

After passing through the strainers the compound is passed rough a refiner, which is a small mill whose rolls are held very se together. The compound is run through at a thickness of proximately three mils, being passed through several times and ally scraped off the roll as it comes through. It is then bundled and is ready for the warming mill.

The mills are run at constant speed and uniform load. The wer required does not exceed 25 h.p.

Warming. Although the compound is warmed in the mixing ls, it cannot always be used at once in the calenders, and, reover, it is beneficial to the compound to let it season before endering. Warming mills are therefore essential to warm the npound when it finally comes to the calenders. These mills identical with the mixing rolls except that they are equipped h steam-heated rolls. The power required is slightly less than the mixing rolls.

ubing. When the article to be produced is tubular or ring-ped the compound is forced through tubes. This machine imilar to a strainer excepting that instead of a screen and orated plate the machine is fitted with a disk which delivers compound in the form of a tube.

he speed and power requirements approximate those of a iner.

alendering. Practically all rubber compounds, with the excep- of those run through tubes and for the manufacture of led articles, are sheeted in a calender.

nis machine has a series of rolls two or four in number nged one over the other, between which the compound is ed to form a sheet. The surface of the rolls is finished smooth he space between the rolls is adjustable to a very fine degree. rolls are fitted with steam and water connection to heat or the compound as required.

The power required to drive a calender varies over a wide range depending on the character of the compound, thickness, width and speed. The speed is limited to that at which the compound can be run without blistering or the forming of a rough surface. When the calender is started up with cold rolls the permissible speed is higher than after the cooling rolls become heated. As these rolls become heated, it is necessary, in order to obtain the desired surface of the sheet, to reduce the speed. A fine speed graduation is therefore necessary to maintain a maximum output. The torque required depends upon the thickness and material and there are so many combinations possible together with the speed requirements that it is difficult to formulate any rule to determine the power. The motor must be large enough to meet the extreme conditions.

From a number of tests made it is found that an 18-in. (45.6-cm.) diameter, 40-in. (1-m.) face, three-roll calender running at a surface speed of 37 ft. (11.2 m.) per minute, requires an average of 20 h.p. A 24-in. (60-cm.) diameter, 48-in. (1.2-m.) face three-roll calender running at a surface speed of 35 ft. (10.6 m.) per minute requires an average of 35 h.p. and a 22-in. (55.8–cm.) diameter, 65-in. (1.64-m.) face, three-roll calender running at a surface speed of 36 feet. (10.9 m.) per minute requires an average of 45 h.p.

Some compounds that are run through the calender in successive layers which build up to ½ inch (1.27 cm.) or even ¾ in. (1.9 cm.) must be run at approximately 20 ft. (6 m.) per minute, while for " friction " work the speed of the driven roll may be 80 ft. (24.3 m.) per minute. The thick sheets will require slightly greater torque than the average thickness, while the torque for so-called " friction " work is considerably less.

The term frictioning is applied to that process performed by a calender in forcing a soft rubber compound into the meshes of cotton fabric. It is preliminary to the skimming or coating of the fabric. The rubber compound is very soft and plastic and is rubbed in by the action of the driven roll, which travels at a faster speed than the roll carrying the fabric.

As the compound and fabric are fed through in a continuous sheet the power required for a given material, thickness and width is quite uniform.

Motor Characteristics

In considering the power and speed requirements of the different machines, it is seen that the mills for working up the rubber

and mixing it to form the various compounds, call for extreme overloads but of short duration. By grouping these mills and driving by a single motor the load peaks can be reduced. Instead of the maximum values being 200 per cent of the average, it has been determined that this can be reduced to 150 per cent by driving with one motor a group of six mills used for masticating, mixing and warming.

Where individual drive is used, alternating-current polyphase squirrel cage motors are best suited to carry the high load peaks. By grouping the mills, a motor of a smaller capacity than the aggregate of the individual motors can be employed. Moreover, synchronous motors can then be installed and assist in correcting the power factor of the general power load. The mills are generally equipped with jaw clutches which can be open or closed while the shaft is running. The synchronous motor can thus be disconnected from the mills at starting. The selection of squirrel cage or wound rotor induction motor depends upon the local starting restrictions, as the squirrel cage motor will easily bring the shaft up to speed even with all mills connected.

Direct-current motors are sometimes used when this is the power available, but they are more expensive and not so well suited to the load conditions.

The calenders, as mentioned, require close speed control over a range of four to one. This can best be accomplished by a direct-current motor, which is the general practise. A number of schemes have been employed to accomplish this. Among them might be mentioned the multi-voltage and adjustable voltage methods.

The motor is excited at constant field strength and the armature supplied with a variable voltage. This variable voltage can be produced by a series of different voltage generators or by a rotary compensator or booster set.

A modification of the preceding is a three-wire, two-voltage source of armature supply combined with adjustable speed by field control. The first-mentioned methods produce a wide speed range but are expensive because of the number of machines required for each calender. The second method produces a less speed range but is less expensive, particularly where a large number of calenders are installed.

With the more recent general application of commutating poles to direct-current motors a greater speed range is permissible with constant armature voltage and varying field strengths.

This last-mentioned method results in the simplest equipment

as a whole. The motor must be larger but is therefore more substantial, while the control can be made extremely simple, or it can be made entirely automatic, thus calling for a minimum of attention and care from the operator.

The tubers also require a direct-current motor and the last-mentioned method of speed control is particularly adapted to these machines.

As the power to drive the mills is by far the greatest portion of the total power, alternating current will generally be selected. This therefore requires a motor-generator set or synchronous converter to deliver direct current to the calenders and tubers. These machines can be used to correct the power factor of the general power circuit.

Motor Control

As the motors to drive the mills are run at constant speed, starting devices only are required. A speed-controlling device must, however, be furnished with the motors driving the tubers and calenders. The former machines are simple in operation and a controller for hand operation which combines starting and speed adjustment is sufficient. The calenders, however, require closer attention and must be capable of starting and stopping by the simplest means on the part of the operator. This is best met by a control which enables the operator to bring the calender up to speed by moving the controller handle around to obtain the desired speed. Automatic acceleration should be provided to limit the current input while the controller handle is being moved around. It should then be possible to shut the calender down by pushing a button located on the calender. The speed of the calender should be retarded by dynamic braking of the motor. This is to provide a safety feature in respect to the operator in case his hand should be caught between the rolls. Also, it is desirable to stop quickly to save material otherwise wasted by the coasting of the motor. It should then be possible to bring the calender up to the same speed as before by pushing a button on the calender. Means should be provided for reversing the direction of rotation of the motor to assist in manipulating the calender and also in case anything should be caught between the rolls and it becomes necessary to back it out. The control should also include overload and low voltage release features and be immune from damage to itself or the motor in case the operator fails to close or open the proper switches.

DISCUSSION ON "THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING" (NEWBURY), "COMMUTATING POLE SATURATION IN DIRECT-CURRENT MACHINES" (STOKES), "CONSTANT VOLTAGE TRANSMISSION" (DWIGHT) AND "THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS" (PARKER), COOPERSTOWN, NEW YORK, JUNE 25, 1913.

William J. Foster: The self-starting synchronous motor has one bad characteristic and that is the induced potential across the field terminals. It is something which exists in the nature of the apparatus. Of course, if we keep down the number of turns in the field winding, we always can help out in the matter of induced potential, but, as is stated by Mr. Newbury, it is not always convenient to do this. As a general rule, 125 volts has been regarded as standard, and we can design and wind the fields and insulate them so as to take care, ordinarily, of 125-volt windings, but when it comes to 250 volts it begins to be a serious matter. The insulation problem is serious. In such cases I have known of this scheme of short-circuiting the field to have been the practical solution of the problem, but in general, as pointed out by the author, the short-circuiting of the field detracts from the starting torque per input. That being the case, it is extremely desirable to excite at lower potential.

There is a particular use which can be made of the short-circuited field that I have known to have been resorted to in a number of cases of motors that have an increasing torque from rest to synchronous speed, and that is to short-circuit the field when about two-thirds speed has been attained. By doing that the torque can somewhat be increased at the higher speed, before you reach the point where excitation can be applied.

I think there are many places where synchronous motors are now installed and some difficulty, perhaps, is experienced in starting up at the pulling-in point, where by installing a resistance and short-circuiting the field much better results can be obtained.

August H. Kruesi: I want to suggest that the author give us the number of slots per pole, the radial depth of air gap and the number of bars in the short-circuiting winding for both machines so that we can tell to what extent the performance depends upon the particular design of the machine tested.

F. D. Newbury: The number of armature slots per pole is twelve, and the radial depth of air gap 3/16 in. (4.76 mm.) The number of damper bars per pole is seven and the damper winding is of the same type as shown in Fig. 1. The armature slot pitch is 0.88 in. (22.35 mm.) and the damper slot pitch is 1.15 in. (29.2 mm.)

H. M. Hobart: Mr. Stokes's paper draws attention to one of the greatest difficulties in connection with the design of machines with commutating poles. The commutating pole certainly

has been of very great service in improving the design of commutating machinery, but there are two sides to the matter and it has always seemed to me that it should not be used to any greater extent than is necessary for the accomplishment of the purpose for which it is put there. At its advent, designers used it to a very great extent and overdid the thing. The reasoning was that since with the commutating pole one could offset very large reactance voltages in the coil undergoing commutation, there was no need for any great subdivision of the commutator. It was considered that by having fewer segments and cheapening the construction of the commutator one could get as good results by neutralising the reactance voltage in the short-circuited coil by appropriately designed commutating poles, but it soon became apparent that there would be a tremendous magnetic leakage from these small commutating poles to the large main poles. Some designers appreciated that, but they were in a small minority. Most designers made the commutating poles the full length of the machine, but, as Mr. Stokes points out, there is 200 or 300 per cent magnetic leakage under these circumstances, unless you are quite careful in the design of the machine.

I considered right from the beginning, that the use of the commutating pole should be as follows: to design the machine as well as you could, quite aside from the commutating pole, and then put in enough commutating pole to neutralize the amount of reactance voltage, which you ordinarily have in the machine, or as much of it as is necessary to insure good commutation. My experience has been that it has usually worked out admirably to have the commutating pole extend only a very short distance in a direction parallel to the shaft. Make it as short as possible for the requirements. One should follow the procedure of first designing the machine as good as possible, without any reference to the intention which you have in reserve of adding the commutating pole.

Designers have been tempted to employ high reactance voltages. If, for example, a machine were planned with a reactance of 4 volts in the short-circuited coil, it might require that the commutating pole should extend the full width of the machine. If, however, a better design had been employed and the reactance voltage had been limited to 2 volts, then the machine could have been fitted with commutating poles of only half as great a length. This would have resulted in reducing the magnetic leakage and in less obstruction to the circulation of air amongst the poles.

Even at this late date, although the commutating pole has been used extensively for 10 years, there is still great need to emphasize this viewpoint. I am interested to see that the matter is being reduced to quantitative constants that will be of great aid, I have no doubt, to the designer.

F. D. Newbury: My own experience with direct-current design has been largely second-hand, and the experience I have

ı connection with alternating-current problems. seemed to me that designers of direct-current been more inclined to approach their problems :al methods than have designers of alternating- .ery. Possibly this is due to their older ex- he further distance they are away, in their the simple fundamentals. That at least has e tendency.

er pleasure, therefore to note that in the present r has got down to fundamentals, has made up m the results of careful experiment, and has subject from the scientific and physical stand- n from the empirical.

er is primarily of interest to the designer, it is, nterest to the men using direct-current apparatus. and particular relation between the commuta- ion and the ability of a given machine to with- rloads. It is, of course, on overloads that the commutating pole becomes apparent and the 1 reactance volts cause dangerous sparking. it machines, even the compensated type, will ort circuit where the current will be anything mes full load current. I have had many tests e borne out the statement that most machines riously with currents from five to ten times full hose machines in which the commutating poles lly proportioned, and more important still, as ted out, machines in which the reactance volts a minimum are the machines that will with- t shocks and behave best on short circuits.

: In connection with Mr. Hobart's remarks, ery extensive series of tests which showed clearly ained by the use of commutating poles. This determine if the commutating pole had any nstant speed motor design. For some time its ustable speed motors had been conceded. A nber of representative motors of various makes ance tests under these three conditions:

ıd normal voltage.

ıd 10 per cent below normal voltage.

ormal voltage and 15 per cent increased speed shunt field.

ted were all of the non-commutating pole type ion (1) practically all gave good results, while (2) and (3) burning and blackening of the com- d in time. Similar tests on a series of com- otors showed that under all three conditions, showed no signs of blackening or burning. ıd (3) are not to be considered abnormal and for and the commutating pole when properly s care of them perfectly.

H. M. Hobart: Commutating poles are used as an antidote for certain troubles, and if the antidote is used to too great an extent it may cause a condition which is worse than that which it was designed to cure. That is the point.

John M. Hipple: There are two ways of considering the commutating pole, one as an antidote for commutation troubles and another as a prime factor in design. In my opinion it has a proper and very important field as a prime factor in design, just as in the non-commutating pole motor the saturated pole tip is often used as a prime factor.

H. E. Stokes: In regard to Mr. Hobart's remarks on the short interpoles, it seems to be the general experience that it is well to make them shorter than the armature, say about 50 or 60 per cent of the length of the armature, and that has the effect of permitting the heat to get away from the armatures as Mr. Hobart pointed out. Something can be done to get away from the leakage question by making the interpole shorter, as regards the armature, and lengthening it up near the frame.

In regard to what Mr. Newbury had to say about machines flashing over, whether they are compensated or not, that is mostly due to the commutating pole flux lagging behind the reactance voltage, which causes a flash-over which can scarcely be taken care of by the commutator form.

F. D. Newbury: Mr. Dwight's paper presents very clearly the advantages of synchronous condensers in holding constant voltage at the end of a long transmission line. There is one application which I understand has already been made where such a use of synchronous condensers was a necessity—the combination of a long line at high voltage and at high frequency so that operation with a light load at the receiving end made it absolutely necessary to install such synchronous condensers in order to hold the voltage down to normal, due primarily, of course, to the small generating capacity in comparison with the length of the line. In that case synchronous condensers of half the capacity of the generators at the generating station were installed. That is a special application of the general plan advanced by Mr. Dwight, and I am quite sure merely points the way to a more general use of such synchronous condensers. As Mr. Dwight points out, the use of such a large additional generator capacity can only be justified in the case of long lines, where the cost of the line will be a more important item in the total cost than the cost of the main and substation machinery.

Mr. Dwight refers to railway work as possibly the single exception to the general use of 60 cycles. I would point out that it is becoming more and more frequent to use 60 cycles for railway work, employing 60-cycle synchronous converters. In the work of one of the larger manufacturing companies it has become very apparent that the use of synchronous converters, in the smaller sizes up to 1000 kw., has gradually shifted from 25 cycles to 60 cycles; whereas a few years ago the 500-kw., 25-cycle

example was built in large numbers, at the present
:ycle converter is the more usual machine, so that
Dwight's single exception can be largely eliminated.
.t also has some misgivings as to the ability of such
condensers operating at very low excitation for
ding current at no-load. I do not think any such
:ist—practically any synchronous motor with a
er winding will hold up the voltage on poorly reg-
ıs at no load and very small excitation.
)wight if in his table on page 1556 the power factor
:ing station has been taken into account in deter-
e and cost of the two schemes. In one case it is given
, while in the other it is given as 89 per cent. This
10 per cent in the kv-a. capacity will increase the
onstant voltage method, but it is a minor point in
th the total saving incident to the system.

amson: Mr. Newbury's paper is an exceedingly
nteresting one, and particularly so to those engaged
of self-starting synchronous motors. The various
;ive a complete picture of the actions that take
the different stages of starting and make many
vhich, while known to exist were not heretofore
tood. Some of the features brought out by Mr.
; touched on during the discussion of these motors
of the Institute held in April, 1912, in Pittsburgh,
ıt paper clears up a number of points brought up

ry's conclusions drawn as they are from the very
of oscillograms leave little room for discussion.
esults obtained show that this class of motor is
ormances at starting and pulling into synchronism
the limits usually considered possible.
starting from rest, the difference noted between
eloped with the rotor winding open and closed is
ss than most machines that have come under my
ver, this is something that depends very largely
of the machine, and I agree with Mr. Newbury
cases where a very high starting torque is desired
igh-resistance squirrel cage is used, it is possible
to start with the field short-circuited through
ough it may be necessary to open the field circuit
to prevent locking at half speed. I understand
ıes tested by Mr. Newbury had a laminated rotor
hines having a cast-steel or cast-iron spider, the
d in the open field winding is considerably less
field structure is laminated throughout.
t feature brought out is that it is not necessary
rting points, provided the most favorable proced-
when starting; and the deductions drawn from
s show the methods of starting and amount of

excitation best suited to different starting conditions. Before the influence of field excitation on the momentary rush of current at change-over was discovered, there was considerable trouble with these motors due to tripping circuit breakers. The oscillograms show plainly why this was so.

To many who have not experimented with this class of motor it will appear surprising that Mr. Newbury was able to pull loads practically equal to full load into synchronism. However, this is quite possible, although the large current required to do it must not be lost sight of, and in many cases this would preclude the use of the synchronous motor on such large starting load, unless of moderate size or operated on large systems where the current at starting was not objectionable. Fortunately, however, in many of the largest applications it is possible to reduce the pull-in torque required to a fraction of full load so that the starting current can be kept down. For example, air compressors can be unloaded, and centrifugal pumps can often be started with the discharge valve closed. Many of the early self-starting motors were made from parts originally designed for alternators, and did not give the best starting performance possible; but with careful design along the well-established lines of squirrel cage induction motors, starting performances comparing favorably with the induction motor can be obtained.

Mr. Newbury's paper deals with motors of the salient pole type and it may be of interest to mention some tests recently made on a small turbo-generator run as a three-phase self-starting motor. There has been, at least among some engineers, the opinion that the pulling-in effect is due partly to the fact that the poles are sharply defined, and that a machine having a cylindrical rotor without projecting poles and with a distributed field winding would be deficient in pull-in torque. Some tests were made with a small 125-kv-a., 2300-volt, 31.2-ampere, 3600-rev.per. min. turbo-generator having a smooth cylindrical rotor with 36 slots uniformly spaced around the circumference. The retaining wedges for the coils were of brass, and made connections at each end with bronze end bells, thus forming a uniformly distributed squirrel-cage.

It was found that with the field circuit open, this machine started with 280 volts applied to the stator and came up to speed in 54 seconds while drawing a current of 67.8 amperes. That is, the motor started on approximately $12\frac{1}{2}$ per cent voltage and 2.2 times full load current. The power factor at starting was between 45 and 50 per cent. With the field short-circuited, there was very little difference in the starting performance, the voltage and current being practically the same as before. Tests were also made with various resistances ranging from 0.9 ohm to 22.4 ohms in the field, but there was very little change noticeable in the starting performance.

Some tests were also made to determine the load that could be pulled in. With 1130 volts (about $\frac{1}{2}$ voltage) applied to

stator and with a field current of 19 amperes, it was possible to pull in a load of 32 kw. or about $25\frac{1}{2}$ per cent of the rated output. The stator current just before synchronizing was 40 amperes or 1.28 times full load. Since the torque may be taken as approximately proportional to the square of the applied voltage, it is seen that this machine would probably pull in nearly full load if thrown over to full voltage. This was not tried in these tests on account of the loading arrangements not being suitable, but it is evident that the round rotor motor can pull in loads comparable with those handled by the salient pole machine.

H. M. Hobart: I share Mr. Williamson's views, and I am hoping that Mr. Newbury's paper will rather stir things up and make people take a little new courage in approaching the subject of the design of synchronous motors. It has gotten into a terrible rut, it seems to me. This is partly due to the cause to which Mr. Williamson alluded. Matters have drifted into having the design of synchronous motors handled by the same departments that handle low-speed alternating-current generators. Any proposition to consider the design of synchronous motors along the lines of the design of induction motors has always been handicapped by the necessity of a change of hands, as to who should design it, and bring about the evolution of the synchronous motor into a decent machine. It is at present an absurd caricature of what it might be and the tantalizing part of it is that there are several perfectly serviceable methods ready and waiting to be used, but you cannot get anybody to look at these methods, or incorporate them in their designs, simply because they are following the old cut-and-dried methods, and everybody turns a deaf ear to any propositions for improvement.

Mr. Williamson alluded to some very interesting departures which he has had in hand and which it seems to me should offer much promise, but there are also other methods which would also serve to render the synchronous motor an admirable machine and make of it a machine which could be more widely used, for the reason that it will tend to decrease the price at which power can be provided to the consumer, in many cases, because you can run your synchronous motor with a leading power factor. That is a very important point indeed.

I believe that the synchronous motor can be used to great advantage in much smaller sizes than has heretofore been considered desirable, in sizes which will lap over into the field that has been generally held by common consent to belong to the induction motor. If only the synchronous motor could be designed by induction motor designers, working on the lines which have enabled them to see just what is needed for these starting and running-up conditions, the result would be for the good.

The induction motor has the fault that if you give it high starting torque, with the squirrel-cage variety, that will be accompanied by low efficiency and considerable heating. It must have high resistance in the squirrel-cage rotor, for the purpose

of giving the starting torque required in many special cases. This is an inherent characteristic of the motor. But in the case of the synchronous motor you can, in a sense, leave it behind when you synchronize the machine and have a highly efficient and cool-running machine for ordinary running, yet at the same time have a high starting torque, so that the synchronous motor, instead of being inferior in regard to its ability to have good starting torque characteristics, has an advantage over the induction motor in those respects. It ought to be associated in our minds as a characteristic of synchronous motors that they can be given *better* starting torque than induction motors, whereas we have just the other notion.

In reading over Mr. Dwight's paper, far too hurriedly, for so excellent a paper, it seems to me the nature of the results, and the careful calculations which he made, bring out much more strongly than they ever have heretofore been brought out, the advantages to be derived from this use of synchronous condensers in connection with long-distance transmission. The result is that the differences, expressed in percentages, are tremendous as regards extending the limitations. Why are we going to 100,000 and 150,000 volts? Because we have exhausted the possibilities of lower voltages in the matter of reaching out over wide areas and delivering energy at the limits of the system at a price which can compete with local plants. If, as Mr. Dwight's figures appear to show, you can, with a given voltage, if you operate on this principle, extend these limits 50 per cent, so that you can carry out at 100,000 volts, an undertaking in connection with which you would otherwise have to resort to 150,000 volts, you have just so far extended the limits, and when you are driven up to 150,000 volts, or higher, this further extension of the limits is still at hand.

As regards the amount of power transmitted, the distance to which it can be transmitted, and the price at which it can be delivered at a great distance, it would appear from Mr. Dwight's figures that the constant voltage method of working will lead to great extensions of the possibilities in connection with the electrical transmission of energy. It seems to me that the conclusions are very fairly and clearly stated, and that the paper is for this reason a very valuable one.

Lee Hagood: I have been very much interested in Mr. Dwight's paper. It struck me that the most interesting feature of it was that he could work out so many results and come to such valuable conclusions by such very simple methods.

A short time ago I was identified with the design of a system in which we were laying out a 110,000-volt transmission line, and our starting point which had to be settled was: what would be the size of our synchronous condensers. The necessity for this arose because our load was chiefly an inductive one, and we could not proceed with the design of the system until we settled upon the difference in voltage between the generating and receiving

stations at full load. Until this was settled, we were unable to fix the voltages and taps for the transformers and the kv-a. ratings to give our generators and transformers. Another point of considerable importance was the size of conductor. As the transmission line was very long, it was important, on account of expense, to use as small a conductor as was consistent with good engineering. All of these points revolve around the question of voltage difference maintained between the generating and receiving stations, because the power factor and efficiencies of the line have fixed relations depending upon the kilowatt load for a given voltage difference and line constants. The question of the size of synchronous condenser is dependent upon this and also upon the power factor of the load.

I note that Mr. Dwight does not take into consideration the charging current of the line. I think this can be neglected for lines under 60,000 volts, but I think for all long lines above this, it should be included.

(The lantern slides and explanations of them, included in Mr. Hagood's discussion, will not be reproduced here, as they were used in connection with a paper presented before the Los Angeles and the San Francisco Sections, entitled *Operation of Transmission Lines*. It is published in this volume, p. 855.)

N. E. Funk: Referring to Mr. Parker's paper, I wish to call attention to the fact that even though we consider raising the power factor from a low value to unity, which is the worst condition so far as cost is concerned that can be imposed upon a synchronous condenser installation, the cost balance will still be on the right side of the ledger, as the following table will show.

Load.	P. F. of load	P. F. of Line	Syn. motor capacity.	Gen. capacity	Cost of gen.	Cost of motors	Cost per kw. of load	Savings per kw. of load
100	80%	80%	0	137.5	$10,312.50	0	$103.125	
100	80%	100%	60	104.93	7,869.75	$600	84.69	$18.435
129	80%	100%	77.4	137.5	10,312.50	774	85.80	20.00
129	80%	80%	0	182.1	13,657.50	0	105.80	

The above table is based on a 10 per cent line drop in the first instance and the same line used in the other cases. Cost per kw., generators = $75, cost per kw., motors = $10. The first two lines show the saving in generator capacity by using synchronous motors. The last two lines show the increased cost of generators required without synchronous motors to load the generators in the first line with synchronous motors.

Mr. Parker says: "Where the synchronous quadrature demand can be made in excess of the lagging quadrature demand from induction motors, it then becomes desirable to put inductance in series with the feeder, thereby overcoming the drop due to the in-phase amperes operating in conjunction with the line

resistance." By doing this the drop is decreased, but at the expense of a lower power factor, which will increase the kv-a. capacity of the generators faster than the decrease in drop decreases it. The idea is that where a transmission problem involves the use of synchronous machines to control power factor it is much better to favor the generating station, as it is the most expensive part of the equipment.

M. T. Crawford: Mr. Dwight states that in commercial practise with short lines, constant voltage transmission is worth while merely on account of the improvement in service. In a system where the average load conditions are found, there are always a number of feeders supplying industrial power and railways in which a voltage variation of 10 per cent is within the limits of good service. For the remaining feeders supplying light and small power, automatic feeder regulators can be installed and operated at a much lower cost than the synchronous condenser installation for constant voltage operation. It might thus appear that where the lines are fairly short and no marked saving can be made by their increased carrying capacity, separate automatic regulation might generally be more economical, especially as it avoids increasing the amount of apparatus and complication of the high-tension system.

Henry W. Peck: An idea which may be of interest occurs to me, viz., that possibly we can use synchronous motor exciting apparatus to greater advantage at the distributing end of some of our lines than at the generating station end. In Schenectady, where we purchase 40-cycle power and transform it to 60-cycle, we have several small machines in the generating station which we practically never use, and as soon as I return home I intend to look up the matter as to whether or not we can use these motor-generator sets advantageously as synchronous condensers on some of our long feeders.

One line which I have particularly in mind supplies an amusement park about five miles (8 km.) out of the city, the line being about ten miles (16 km.) long. When the park is not being run we get reasonably good regulation on the line, but when the park is in operation we have a good many complaints regarding our service. I believe we could advantageously take some of our synchronous generating equipment and make better use for it at the end of the line. I realize in making this suggestion that the present machine would not be ideal for that service, but when you consider the scrap value of such a machine, which is all that you could get for it, it means the tying up of very little investment for the sake of this regulation. If this idea is not practicable and this plan will not apply I will be glad if some of the designing engineers will tell me why it will not apply.

F. C. Caldwell: What is the comparative effectiveness of synchronous machines, such as synchronous condensers, when running at full load, running at half load, and running light?

F. D. Newbury: I think that Mr. Caldwell's question can be best answered by reference to the familiar right-angle triangle

of which one side represents the energy load carried by the motor in any particular case; the side at right angles to this, represents the leading wattless kv-a. supplied to the supply line; and the resultant of these two represents the total kv-a. load on the motor. If the energy and wattless loads are equal, (representing the total load by 100 per cent), each will be equal to 71 per cent. Thus, if these two functions were performed by separate motors, the two motors would require a combined capacity of 142 per cent. If the ratio of energy load to the total load were smaller—say, 60 per cent—the wattless component would be 80 per cent to load the motor up to 100 per cent. Thus 140 per cent "service" is obtained as compared with 142 per cent in the previous example. It will be found that the maximum service will be obtained from a given motor when the energy and wattless components are equal—in other words, when the energy load is 71 per cent of the total. This, of course, is the same as 71 per cent power factor.

Burton McCollum: Mr. Dwight points out in a very effective manner some of the advantages that accrue from the use of synchronous condensers in connection with constant voltage transmission, particularly the operating advantages, and he also cites some rather remarkable economies, particularly where he gives some comparative cost data, but I believe that in most cases these economies are largely apparent only.

In the second comparison for the 100-mile (160.9-km.) transmission line he makes a comparison on a 54,000-kw. transmission, and reduces the efficiency of transmission from 95 per cent to 91 per cent, but by so doing he is able to bring about an economy of something like 26 per cent in the initial installation. Now, if we figure the money value of the increased energy loss that results, using the rather liberal line loss factor of 0.3., (the ratio of the average square to the maximum square) and taking one half a cent per kw-hr. for the value of the energy, we find it figures out at $27,500 a year as the value of the energy loss, which is more than 10 per cent of the saving that results in the line construction.

A similar statement can be made in regard to the first comparison, although the results are somewhat less marked. This statement would of course apply to a steam plant transmission line rather than a water power transmission. In the case of the water power plant the value of the energy lost would be less, but the line loss factor would usually be larger, which would partly offset the lower value of power.

I do not want to detract in any way from the importance of the paper by Mr. Dwight, because I regard it as an important development in engineering, but I feel that the advantages that are to be looked for are for the most part advantages in improved operating conditions rather than in increased economies.

H. B. Dwight: Mr. Parker's paper on the application of synchronous motors in the distribution of power in cities, shows

that this type of apparatus produces desirable economies and improvements in operating conditions in this class of work. As he points out, the supply company is benefited rather than the customers, and accordingly the latter must be compensated for installing the more expensive synchronous machines. He suggests making compensation by charging for the kilovolt-amperes supplied, thus influencing each customer to operate at all times as closely as possible to 100 per cent power factor.

Although it is evident that compensation must be made to secure the installation of synchronous motors, there are two objections to the above method of charging for electric power, namely, that the kilovolt-amperes are very difficult to meter, and that this method does not secure the best possible benefits from the synchronous motors according to the real needs of the supply company. The benefits may be of two kinds; first, reducing the kv-a. load on the generators, and second, reducing the cost of feeders by improving the voltage regulation. For the first, the synchronous motors should operate as strongly leading as possible at all times, but for reducing the necessary cost of feeders, which is often comparable to the cost of generators and which is also often increased by poor voltage regulation, adjustment of the synchronous motors is necessary. This is well accomplished by automatic regulators, as mentioned in Mr. Parker's paper. The saving in cost of feeders can also be made by installing a high-voltage transformer. Neither of these methods of operating the motors corresponds to keeping the customer's power factor at 100 per cent. It is accordingly better not to charge for the kilovolt-amperes, but to charge for the kilowatts, as usual, and to have a separate provision in the contract giving a bonus to the customer for operation of the motors either according to instructions from the company, or by automatic regulators.

Regarding the paper on constant-voltage transmission, Mr. Newbury, I believe, mentioned that for railway work the frequency of 60 cycles is being used to an increasing extent. This is true where alternating current is used to supply direct current railways, since the 60-cycle synchronous converter is now becoming more popular. But for single-phase and three-phase railways, the frequency of 25 cycles is used, owing to the characteristics of the motors.

The same speaker asked if allowance had been made for the ten per cent difference in the power factor of the generators in the 200-mile (321.8-km.) line. The item was not written down in the comparison as it would amount to only about $20,000. A more important item is the cost of energy for extra line losses with the constant-voltage system, as mentioned by Mr. McCollum. For a water-power plant, this item is equal to the cost of machinery to supply the extra losses at peak load. At $50 per kw. this amounts to about $200,000 for the 100-mile (160.9 km.) line which Mr. McCollum took up. Against this item, there

be taken into account the two other items not put into the because of their indefiniteness. These are the saving in ›st of land and the value of the improvement in service, ıey balance fairly well the cost of power for extra losses. urpose of the cost comparisons in the paper is to point out ›r almost any installation it is worth while figuring up costs if synchronous condensers are not profitable.

curves shown by Mr. Hagood were very interesting and just one small matter to bring out regarding them. The ty of the synchronous condensers was plotted always as ght line. You will notice in the chart, Fig. 5, of the con- voltage paper, that the capacity of synchronous conden- quired is a curved line, and its curvature puts a theoretical ›n the amount of power which can be sent over a trans- n line. In the case considered, of the 200-mile (321.8-km.) ıe limit is only about 25 per cent more than the amount ver assumed for full load. The curvature of that line is tly worth figuring up in long distance work. It is a peculiar effect that there is this theoretical limit to the capacity of a transmission line of a certain voltage, which be overcome by synchronous condensers nor anything else.

Hagood: I cannot prove these curves mathematically, ıave tried a number of them and found them all straight

3. Dwight: I have no doubt that the points you have , as you say, are correct, and as far as you have gone along , it is practically straight. But the indication in plotting ght line is that unlimited power could be transmitted over if enough synchronous motors were added. The limit, r, is struck very soon by this theoretical consideration will show up if you try to put 50 per cent more power over nsmission line. You would run into the limit with your tions in the same way.

Hagood: I do not agree with you.

Lincoln: I inquire of Mr. Newbury what the starting is when synchronizing on the three types of rotors shown 1514. The curve is interesting, and it appears that the torque of the rotor with the brass damper windings is er high resistance, which is much greater at any particular than in the case of the starting torque at low resistance, question is, which is the type of rotor that will come in ›nism with the least amount of current? Is it the brass r the low-resistance copper rotor?

Newbury: To answer Mr. Lincoln's question first; re two entirely distinct actions to be considered—two different sets of characteristics. The copper damper which shows the lowest torque at starting will of course ıe lowest torque as long as the motor is operating as an on motor. The torque at which a given motor will pull ıchronism depends on the torque that results in a certain

slip. There is a limiting slip, that may be one per cent or two per cent, beyond which the motor is incapable of pulling over from the highest induction motor speed into the true synchronous speed. Therefore the torque, that a given motor will pull in, will depend on the torque that can be pulled by the motor with a given slip. Therefore, the motor with the lowest resistance damper winding will carry the most load with this limiting slip, and consequently will pull into synchronism with the largest load. On the other hand the high resistance winding will develop the largest torque at the lowest speeds as in any induction motor.

J. C. Lincoln: If there was contained in the paper a complete speed-torque curve, would the torque of the lower resistance copper-wound rotor be greater or less at speeds just under synchronism than the torque of the higher resistance brass-wound rotor? It is very evident from the curve shown in Fig. 9 that at low speeds the brass-wound rotors have a very much higher torque than the low-resistance copper-wound rotors. It would seem to me that, at the higher speeds, just under synchronism, the lower resistance copper-wound rotor would have a higher torque than the higher resistance brass-wound rotor, and therefore that a synchronous motor provided with a lower resistance copper-wound rotor would pull into synchronism a larger load than the high resistance brass-wound rotor. I would like to ask the author of the paper if that is the case.

F. D. Newbury: The torque of the low-resistance rotor would be greatest at the highest speed at which the motor operates as an induction motor and will pull into synchronous speed.

J. C. Lincoln: That would amount to the same thing.

F. D. Newbury: Mr. Williamson spoke of the paper on the synchronous motor which was presented at the Pittsburgh meeting of the Institute last year. The admirable paper by Mr. Fechheimer was the starting-point of my own paper, since at that meeting the discussion was not at all favorable to starting with the field circuit closed. It may not indicate any change in the opinion of the members present, but simply indicate a change in audience, that the sentiment expressed at this meeting has been in the opposite direction.

As Mr. Williamson pointed out, I think the tests show that two starting voltages are not necessary, but I would qualify that in this way—that they are not necessary, provided proper adjustments are made, but proper adjustments always mean careful and skilful attention, so that the two starting taps are used and are justified for the larger motors, where the consequences of wrong operation would be quite serious.

Mr. Hobart has regretted the lack of attention that has been given to the wound-rotor distributed type of synchronous motor. I think that it is more a lack of results than lack of attention, and the reason for the lack of results is more fundamental than a difference of engineering department organization as Mr. Hobart

suggested. The real reason is brought out by the difference in the magnetizing current required by a well-designed induction motor and a well-designed synchronous motor. In an induction motor the magnetizing current is roughly 30 to 40 per cent of the armature current. In the synchronous motor the magnetizing ampere-turns should be at least one and a half to two times the armature ampere-turns. In order to obtain the necessary exciting ampere-turns on a round rotor synchronous motor a much larger rotor is required than for the salient pole type of synchronous motor or the round rotor type of induction motor. There is a good engineering reason, therefore, for the practically exclusive use of the salient pole type. The same conclusion is reached by a comparison of the weights and costs of salient pole and round rotor types of alternators. I think it is well known that the round rotor type of alternator ordinarily used for turbo-generators means a larger machine and a more expensive machine than the salient pole type and the round rotor type is used because it is the only type sufficiently strong mechanically. The same point was well borne out by comparisons recently made on some 10,000-kilovolt-ampere, 600-rev. per min. waterwheel generators, where the cost of the salient pole type was found to be approximately 50 per cent less than the round rotor type.

M. O. Dell Plain: I believe that the possible advantage to be gained by the average central station through a general use of synchronous motors instead of induction motors on its lines is largely offset by the greatly increased number of motor trouble complaints.

The advantage to be gained by the consumer is a very material one in cases where the central station penalizes a low power factor. This advantage, however, is also offset if the current charge is based directly on the demand. In such cases the present lack of a suitable demand meter results in considering the highest phase kv-a. reading as being the actual demand, and an unbalanced load being the usual condition, the synchronous polyphase load does not produce its fullest effect in lowering the actual charge.

The development of a reliable and inexpensive kilovolt-ampere demand meter would probably eliminate this objection.

Henry W. Peck: I have made a memorandum of two or three points which I will answer. The quality of the service is oftentimes more important than a very slight advantage in maintaining unity power factor at the station. It is not for the sake of the power factor primarily, that Mr. Parker suggests the use of synchronous condensers, but to maintain the service which we are giving to our customers.

Another suggestion was made that the synchronous condenser was in competition with the high-tension transformer. An operating man does not like to see his system separated into different voltages, 2300 volts on one part, 6600 volts on another part, and 13,000 volts on another part. From the opera-

ting point of view it is much simpler to have the synchronous condenser than to step up certain portions of the line and have a great variety of transformers which you must carry in stock so as to be able to supply your customers with these transformers when they want them.

Referring to Mr. Dell Plain's remarks, it is manifestly impossible to put a synchronous motor in every and any installation, regardless of the character of the plant and the man who is running it. In the case cited by Mr. Parker where they use the synchronous motors for pumping, refrigerating plants and similar purposes, they have operating men who are certainly of as high a class as any men we have in our own stations and who can be trained to operate the synchronous motors satisfactorily.

We must consider the economy of such an installation from the point of view of both the customer and the company. The customer must decide if the saving, due to the lower rate for power, is sufficient to warrant him in installing these appliances in his power plant, granting that they are not quite as simple and convenient as the induction motor. The company must decide if the saving and improved service incident to the installation of these appliances are worth the expense represented by the decreased rate for power and by the assumption of such part of the first cost of the machine as is represented by the excess capacity required to handle the wattless load.

As regards metering the kilovolt-amperes, I know that it has been done in one installation which was put in under Mr. Parker's direction, using two meters, a graphic voltmeter and a graphic ammeter. The installation in which this meter was placed was of 600-h.p. capacity, and the cost of these meters, while prohibitive on smaller installations, was by no means prohibitive for one of such large size. If the phase voltages were perfectly balanced there would be no difference in the current in the different legs. Measurements were taken at this installation and it was found that the difference in voltage and current in the different legs was negligible.

N. E. Funk: I did not mean to leave the impression that poor service was to be furnished so that the power station might enjoy the benefits of a high power factor, by any means. What I meant to convey was, that it was the best policy to attempt to get unity power factor rather than leading power factor, which is as bad in so far as generator capacity is concerned as a lagging power factor. In following out this manner of design it is not necessary for the voltage at the receiving end of the line to vary any more than if the voltage were the same at both ends. There are various means of correcting voltage besides that of synchronous condensers, and if it is not possible to favor the generating station and get the proper voltage at the receiver this receiver voltage may be corrected by, say, induction regulators, and the synchronous motors used to annul the lagging component of the load. The thing I had in mind most particularly was the

fact that it was better policy, on account of favoring the generating station and apparatus, which is the most expensive part of the system, to strive toward obtaining unity power factor on the generating station rather than calculating the line for a given voltage at the receiving end and allowing the power factor at the generating station to come what it may.

C. P. **Steinmetz:** The two papers on synchronous motors are very interesting to me, as they give much additional information regarding the usefulness of the synchronous motor as an element of the electrical system, particularly Mr. Newbury's paper with regard to the starting characteristics of the synchronous motor. Synchronous motors, synchronous converters, and synchronous condensers have now been used extensively for over 20 years, and their use is very rapidly increasing. Most of these machines are self-starting, starting from rest with their own power, but still I believe there are a few engineers who doubt the self-starting characteristics of the synchronous motor and consider this as the main disadvantage of the synchronous motor.

The fact is, as brought out by these papers, that the modern synchronous motor, and also its prototypes, are very well able to start from rest and run up to speed and carry considerable load up to speed. They, indeed, take a large current in starting and during acceleration, about as much as the large highly efficient induction motors. The induction motor has never been questioned as to its ability in starting; but the synchronous motor is fully as well self-starting, and sometimes it takes more current and sometimes less current than the squirrel-cage induction motor, as, indeed, it is an induction motor. It differs in these starting characteristics, from the standpoint of the well-known squirrel-cage induction motor of large size, only in the proportioning of the parts. The starting characteristics of the induction motors have been limited by the proportioning of the parts required for getting efficient running, mainly for the purpose of getting high efficiency, high power factor, or low exciting current.

These limitations are not questioned in the induction motor characteristics of the synchronous motor, because the synchronous motor is not expected to operate at speed as an induction motor. Therefore, whatever power factor and efficiency it might have when running at speed as induction motor is entirely immaterial, and therefore in proportioning the induction motor parts of the synchronous motor we are more unrestricted, in choosing those proportions which are capable of giving good starting characteristics, than we are in the large induction motor. That means in many cases it is possible to give to the synchronous motor better starting characteristics than to a large squirrel-cage induction motor. I pointed out some of these things in a previous discussion, for instance, that in the synchronous motor we may have, considering it as an induction motor, an exciting

current of 100 per cent or more without its having any detrimental effect. In the induction motor. obviously such an exciting current would make it commercially inoperative, the reason being, at that time, under the conditions where the synchronous motor acts as an induction motor in starting, the energy current for acceleration is so large and the impedance current is so large that the exciting current does not cut any figures. It is negligible, no matter how much it would be in percentage compared with full load current.

The main differences in the proportioning of the induction motor part of the synchronous motor compared with the induction motor are three. First, the synchronous motor does not have uniform magnetic reluctance in all directions of the rotor, it is minimum in the direction of the field poles, and maximum at right angles thereto while the induction motor has uniform reluctance all around. This is a disadvantage in regard to the starting of the synchronous motor as an induction motor, since it tends to a lack of uniformity of the torque with the relative position, and thereby also tends to low torque points, that is to a tendency of sticking, as it is called, at intermediate speeds, more particularly at half synchronism. Second, the synchronous motor has a very large air gap compared to the air gap used in the induction motor. The induction motor, to get good power factor, low exciting current, must have as small air gap as mechanical construction permits. In the case of the synchronous motor the power factor and the running on light current do not depend on the length of the air gap. Therefore the air gap, in the case of the synchronous motor, is chosen in accordance with very conservative mechanical and other considerations. The large air gap has an advantage in starting, in so far as it tends to give a uniformity of torque. Third, the secondary winding of the synchronous motor, compared with that of the induction motor, is of much higher resistance, which again is an advantage in starting, so, you see, of the three main characteristic differences in the proportioning of the induction motor part of the synchronous motor, one is against but the other two are in favor of high starting torque and the result is that the synchronous motor really starts better than a large high efficiency squirrel-cage induction motor.

The oscillograms shown in Mr. Newbury's paper are extremely interesting in giving the starting characteristics, but from these oscillograms you can see there are many other things which the limitation of space did not allow Mr. Newbury to show. If you look at them you see this more particularly, in the case of the oscillograms of a current, the amplitude of the current, the periodic rise and fall. You see the meaning of that—it is due to the varying magnetic reluctance with the position; maximum current corresponds to maximum reluctance, minimum current to minimum reluctance. Hence the distance from current maximum to current maximum corresponds to the dis-

tance moved by the rotor from one maximum reluctance point to another maximum reluctance point, which means the distance of half a field pole or multiples thereof, or the slip of half a field pole or multiples thereof. That means the space moved through but the frequency of the oscillograms gives the time, and therefore you see from these oscillograms that you can get, from the distance moved by the rotor and the time of motion, the speed-time curve during acceleration, and from the speed-time curve you get the acceleration-time curve, and therefore since acceleration gives you the torque, relatively, or when considering the momentum of the moving mass, then absolutely, you get the torque-speed curve. That means a variation of the torque of the machine from standstill up to synchronism. All the characteristic curves of motion you get from these oscillograms, curves which in the induction motor are difficult to get, because in the induction motor the speed range near maximum torque, is unstable, and characteristics of that range can be derived mainly by connecting the motor with a generator which feeds a direct current motor connected to constant speed shafting and varying the field excitation of the motor which checks the output. This is well known and has many times been described, and in this way you can hold the induction motor at any point of speed, stable or unstable, above or below synchronism, and you can get the complete torque characteristics. The oscillograms of the synchronous motor permit you to arrive at a very definite understanding of the speed-torque characteristics, which in the induction motor you might get, possibly, an exploring winding on the squirrel-cage.

Looking at these oscillograms, you see a number of characteristics which are incidentally mentioned. If you take curve Fig. 2, at the end of the first oscillogram, you see a number of waves with a high and low amplitude alternating for a considerable number of periods there. Apparently the speed was practically constant, which meant a low torque point there, where the motor accelerated slowly, because after a considerable number of cycles there was no acceleration or little acceleration. That apparently corresponds to one-quarter synchronous speed, and later on at about two-thirds the distance of the second curve from the bottom of the page, there was a very large number of cycles where the amplitude is constant, where the machine moved from maximum reluctance point to maximum reluctance point, during one cycle or during half a cycle. During half a cycle it progressed half a field pole. That apparently is half synchronous speed where it tends to drop off a little. The next curve is still exaggerated, but much less prominent at the three-quarter synchronous point, so that if you would construct from the oscillogram the speed-torque characteristic, you would probably be required to introduce a considerable drop in the torque at half synchronism, a moderate drop of torque at one-quarter synchronism, and a further moderate drop of torque at

three-quarters synchronism. This is at the low voltage starting. At higher voltage starting that phenomenon is not so marked, but these oscillograms allow you to study the acceleration curve of the synchronous motor much more closely and control it much better than in the case of the induction motors, where it is more difficult to determine all these characteristics of intermediate speed. We thus see that, as an engineering problem, when it is necessary to provide high efficiency synchronous motors with good starting characteristics what we have really is a much more simple problem than in the case of the high efficiency induction motor. and in my opinion the large synchronous motor is really one of the most important, and most useful elements of the electric system, more so than the induction motor, because instead of spoiling the power factor it may be made to improve the power factor, and instead of interfering with the regulation, making the voltage vary more with the change of load, it controls, or permits the control of the voltage, or acts automatically without any control, by establishing a fixed voltage point due to its excitation. The synchronous motor tends to hold the voltage more nearly constant than the non-inductive load. Many engineers do not yet realize the usefulness and value of a synchronous machine as an element in the electrical system, and therefore I very much appreciate these papers, since they give additional information and undoubtedly will tend to give the synchronous motor a still wider application than it has to-day. The synchronous motor will naturally include the synchronous converter and the synchronous condenser.

W. L. Merrill: I desire to ask Dr. Steinmetz a question in connection with his discussion on synchronous motors, and that is, why he compared the large synchronous condensers or synchronous motors with squirrel-cage induction motors. It has been my experience in such applications where the question has arisen as to whether synchronous motors or induction motors should be used the squirrel cage motor would not even be considered; and it has been the custom always to supply wound rotor collector-ring type of motors in the majority of cases where practically any starting requirements were to be met. In some cases, however, where synchronous motors have been installed to do the work that is successfully being done by wound rotor motors, the operation of the synchronous motors compares favorably with the operation of a fuse after it is blown. I see no reason for comparing the synchronous motor with the squirrel cage induction motor for ordinary industrial applications.

R. B. Williamson: In regard to the point brought up by Mr. Newbury about the wound-rotor type of motor, my idea was not to recommend that type of motor in preference to the salient pole type. The experiment was tried simply to find out if that sort of motor could be started up equally well. Motors of this type might occasionally be used for high speed work. For ordinary service at moderate speeds they would have no material advantage and would be larger for a given output.

F. D. Newbury: I wish to thank Dr. Steinmetz for his contribution to the discussion, particularly, because his discussion brought out a number of points I hoped would be brought out; and I am free to confess that they were not included in the paper for other reasons than lack of space and time, as Dr. Steinmetz was kind enough to suggest.

There is one point in particular I have not been able to understand myself; possibly Dr. Steinmetz can explain it either now or after he has studied the matter a little. Figs. 28 and 29 show exactly the same conditions, but there is a very marked difference in the amplitude of the armature current and field current changes.

C. P. Steinmetz: I wish to think the matter over a little more and cannot give an answer now, but in regard to the former question, as to why I compared the synchronous motor with the squirrel-cage induction motor, the reason was that, when the synchronous motor starts, it starts as a squirrel-cage induction motor, since it is provided with a squirrel-cage, so we would naturally compare that with the squirrel-cage induction motor.

We all realize that there are very many motor applications where we need frequent starting at heavy torque and where we, therefore use the collector-ring induction motor. These applications naturally would not, as a rule, be met by the synchronous motor but in the majority of cases the squirrel-cage induction motor is used and therefore I compared that motor with the synchronous motor. It does not mean that we can use a synchronous motor in every place. The induction motor with collector rings and rheostat armature control has its legitimate and very important field. We may say that since the synchronous motor starts as an induction motor instead of providing a squirrel-cage, a regular winding could be used with a rheostat and improve the starting of the synchronous motor and such was the point I made.

I remember the first big synchronous motor with which I had anything to do, that was in 1893, somewhere on the Pacific coast. The motor is still running. It had a three-phase pole face winding, each winding brought out to a switch, in which a rheostat was connected for starting, but that has never been done since, because there was no need for this complication; and in all the conditions where the synchronous motor was used it was considered all right to start as a high-resistance squirrel-cage motor. That might possibly be done in the case of the synchronous motor by giving it collector rings and the wire-wound induction motor winding. The objection to that is it means a winding which is used only in starting not in running, and that is a complication. If the winding is simple, as in the case of the squirrel-cage motor, which incidentally acts as an amortisseur winding—a damper winding when running at synchronism, —then it is favorable, but it is hardly justifiable in most cases, to go to the complication of an external rheostat, but rather to

use an induction motor with collector rings and rheostat, except in those cases, which may occur, where the synchronous motor is decidedly preferable. I do not recall any cases like this.

J. C. Lincoln: I would like to ask what is Mr. Newbury's experience with reference to the call for high starting torque at low speeds and high starting torque at near synchronous speeds. It happens my experience has been only where we had trouble when it was due to the fact that we had to have pretty high speeds near synchronism, but judging from the paper, and from the curves which are very instructive, I would infer Mr. Newbury's experience has been in cases where high torque was required in starting, and I ask what his experience is as to the ordinary requirements of starting torque, whether a high starting torque is required at starting or near synchronous speed?

F. D. Newbury: Whether the required starting torque is greatest at standstill or synchronous speed depends on the application. The majority of synchronous motors is used in motor generator sets where the largest torque is required at standstill. This may be considerable, as much as 50 per cent, in some cases, of full load torque. In the case of pumps and fans and air compressors, the highest torque is usually required near synchronous speed. In the case of fans it is very hard to shut off the air supply sufficiently so that the torque at full speed is not very near the full load torque of the motor. In the case of pumps where a by-pass can be used, the torque at synchronous speed is considerably reduced. In the case of air compressors, the bulk of the trouble has been at pull-in, and I imagine the absence of trouble in many cases has been due to the fact that the motor was pulled in on full voltage and not starting voltage. Probably the bulk of the synchronous motors have been used for motor generators sets, where the starting torque is the greatest, so that quantitatively the bulk of the trouble has been at standstill.

J. C. Lincoln: With a motor-generator set, would you use a low-resistance winding on the motor?

F. D. Newbury: Not necessarily. Many and perhaps the majority are now built with the brass or high-resistance squirrel-cage windings, illustrating the point Mr. Hobart and Dr. Steinmetz made, that it is possible to obtain the good starting performance of the high resistance secondary with the synchronous motor while it is not possible with the squirrel-cage induction motor. With steam- or water-driven generators now generally used there is little necessity for low-resistance amortisseur windings for prevention of hunting.

H. H. Dewey: Mr. Newbury implied that in the case of large, slow-speed synchronous motors, having a large number of poles, it is a difficult matter to obtain high torque during synchronism. Do I understand that it is harder to obtain it with a machine of this kind than with a high-speed machine having a smaller number of poles, and if so, to what does he attribute the difference?

ewbury: It is decidedly more difficult to get high rque at pull-in, as expressed in percentage of motor th the larger number of poles, and in the case of slow ' air compressors the figure which has been more or ardized by the compressor manufacturer's require- l also by tests, is about 15 per cent; that is, the motors 'p 15 per cent of their normal torque at synchronous have one installation in mind where they would just ıd the tests on the test floor show just about 15 ull in torque. With slow-speed, two, four, and six- rs, used for fans, it is not difficult to pull in at prac- . load torque, if you disregard the starting torque and The reason for this difference is rather intimately with the proportions of the two machines.

Iobart: For a long time salient stator poles were used igh speed generators, but now I think there is a fairly agreement that the windings should be distributed, it is only comparatively recently that there was any reement on that point. Previously the salient pole gly advocated for even very high speeds. I feel that ıld be a closer analysis of the differences in the con- and of the respective fields of usefulness of synchronous d induction motors. If the synchronous motor is to ped on progressive lines the work must be entrusted ho are accustomed to induction motor design.

'ilson: The question has been brought up of the pull- ct with a high resistance motor. I may mention two d recently to do with, where a 2400-h.p. synchronous s connected to some grinding stones for grinding pulp. er in question was of a comparatively new type, where is piled in the hopper, twelve cords of wood pressing ones at all times. This particular motor had a high it had a squirrel-cage winding. I have no way of ıt what the pull-in torque was, but it must have been ble, because there was always a large amount of wood lown on the stone, each stone taking about 1200 h.p. or would start up on $1\frac{3}{4}$ to 2 per cent full load current he line voltage, and seemed to pull into step without o that the high resistance winding at or near synchron- have given fairly high torque.

Steinmetz: Regarding the pull-in torque, I wish to ention to the necessity of some further study of this The phenomenon in the synchronous motor pulling ıchronism is not fully realized by all engineers. It is t so much a question of the load which is to be pulled in estion of momentum. A synchronous motor may have in pulling into synchronism while accelerating without , while it may pull in nicely without any difficulty at , because when pulling in it means it has to jump from given by the induction motor into synchronism, and in

that very short period it has to accelerate the momentum. The acceleration of the momentum is usually very much poorer than the actual load, so that you will find, when studying the pulling in of a synchronous motor, especially a high-speed motor connected to high-momentum apparatus, that the question of load or low load makes practically no difference, or very little difference. What we have to consider in the pulling-in characteristic of the synchronous motor is the momentum which has to be pulled into step, much more than the actual drag or torque.

F. D. Newbury: I do not wish to leave the discussion of round type versus salient type motors where it stands. There is not as much difference between Mr. Williamson and myself as might appear. I still hold to the point that it is a question of cost, and that is a hard question to overcome unless you can overcome it in the direction of a reduction of cost. I do not see how, from theoretical considerations, you can do that. Maybe I am mistaken, but I cannot see it.

There are others, notably Mr. Foster, who have had experience along these lines, and I would like to know from him and others, whether their experience has been the same as mine; that the salient pole type for a given output can be built more cheaply than the round rotor type?

I am entirely in agreement with what Mr. Williamson said in regard to the performance of the round rotor type. There is nothing against its performance; in fact, it has very decided advantages, as Mr. Williamson pointed out; there is uniformity of reluctance so that there is a uniformity of torque in the rotor; the starting performance of the phase-wound induction motor can be obtained by inserting resistance in the external exciting circuit; other decided advantages have led designers to investigate it thoroughly. If my conclusions are wrong, I would be glad to be corrected.

Wm. J. Foster: My experience agrees entirely with Mr. Newbury. That matter has been investigated in a number of cases during my experience of 20 years or more. I think the first synchronous motor I had anything to do with was built with pole faces 85 or 90 per cent of the pole arc, as against the ordinary 65 per cent of the generator. Much of the investigation made along that line, with regard to the design of the synchronous motor, is based on using stock parts of induction motors, since we have the benefit of the cheaper production, due to stock parts, and can easily make, the nesessary modifications in the rotor, with the increased air gap, etc. It has been my experience that we have never been able to work out that type of motor in competition with the salient pole in any size in which synchronous motors are called for. In very small motors, it is often a profitable thing, because there is not demand enough to warrant the development of an entire new salient pole machine. Hence the synchronous motor can be best built from standard induction motor parts in very small sizes.

As to the matter of the characteristics, I am sorry I have not exact data on the subject, but as far as my experience goes it has been in favor of the round rotor, that is, in returns that one gets for the input.

H. M. Hobart: People are usually willing to pay more for a good thing than for a bad thing, if only they can get the good thing.

W. J. Foster: I want to know in what respect it is a good thing as compared with the present motor. Why do you call one good and the other bad?

H. M. Hobart: I call it good because it starts with high torque and runs rapidly up to synchronism with good torque all the way through. These are not characteristics of synchronous motors as at present designed.

Wm. J. Foster: I have built and operated a number of motors of the wound rotor type, but I cannot agree with that statement. It is a question of how to adjust things with relation to the torque, and that is a serious drawback in the synchronous motor. It is right there where investigation has been going on quite actively in the last two or three years as to how to increase the torque.

R. B. Williamson: It seems to me the only reason for building synchronous motors with round rotors is the same reason for which we build generators with round rotors. It is a question of speed. To design a motor for, say, 3600 rev. per min., we would have to use a mechanical construction the same as for a turbogenerator; but for ordinary speeds where we would use a salient pole construction for a generator I should say by all means to use it for the synchronous motor. I do not think there are any great differences in the characteristics; the only thing I had in mind was the question of overcoming the mechanical difficulties at high speed.

W. L. Merrill: The principal point I wanted to bring out by asking Dr. Steinmetz the question I did is that the author of one of the papers appeared to be advocating loading up the central station lines with synchronous motors to the value of 40 or 60 per cent of their total load. My experience in industrial work is that possibly one or two per cent of the industrial applications of motors, with the present type of synchronous motor which we have, could be handled by synchronous motors, and I was afraid from the glowing comparison which Dr. Steinmetz made of the synchronous motor and induction motor that the impression might be gained that they were interchangeable, when as a matter of fact in the sizes which he was discussing no one would consider the question of a squirrel-cage motor any way. If we could get large synchronous motors, involving the characteristics of the form wound induction motors, it would not only be possible, but probable, that the central stations could go to 40 per cent of the total loads with synchronous apparatus.

Wm. J. Foster: I wish to say in connection with the point brought up by Mr. Hobart that if you put in an external resistance with a definite wound rotor, and make use of external resistances, you get excellent results, as far as starting torque goes. You can then cut out the external resistance and switch the excitation on two phases of the rotor winding, leaving the third phase idle, or use one phase against the other two for excitation.

H. M. Hobart: In my first remarks I said there were various ways of improving the motors which were quite available and valuable, but that no one wanted to use them, but I did not go into the question of what those ways were. They related to this question of getting a high torque not only at the moment of starting, but a high torque right straight through into synchronism. I did not feel that it devolved on me to go into the details of these methods on this occasion, since I have already published descriptions* of them. It is an interesting field to which little attention has been given. These methods will be widely used in the future. At present they are opposed in accordance with those general principles always acting when new ideas of value are first brought to attention.

C. P. Steinmetz: I do not think I am prepared to discuss off-hand the last subject which was brought up. We all realize what we have in the synchronous motor is the induction motor start, and also in the starting of the squirrel-cage, as squirrel-cage that is, high resistance in starting and decreasing resistance to a very low resistance at running, and that decrease should be as simple as possible.

In regard to the difference between the definite pole rotor and the uniform reluctance rotor, the main differences in my mind are that the definite pole rotor gives a less uniform starting torque, and if in starting we must consider the momentum torque, the definite pole rotor is inferior in starting, other things being the same, than is the uniform reluctance rotor. Furthermore, the definite pole rotor shows a drop in torque at fractions of synchronism, a certain amount at half synchronism, and less at quarter synchronism, more than the uniform reluctance rotor, which latter very often does not show a drop in the torque curve at all. On the other hand, the definite pole rotor drops into step easier, because it has that additional torque, the tendency of the magnetic lock, therefore in dropping into synchronism the definite pole rotor has the advantage.

At the moment of starting, the synchronous motor of today has ample torque to start any load which it will carry. However, the stopping off at half speed has been a very decided disadvantage in former times in the synchronous motor, but with the introduction of the fairly well distributed squirrel-cage winding, even with the winding local only through a wide field pole,

*See pp. 202 to 212 of "Design of Polyphase Generators and Motors", by H. M. Hobart.

that difficulty has practically vanished, so that as it stands today, on the average there is very little to choose between the definite pole rotor, and the uniform reluctance rotor. You cannot say they are exactly alike, the one is better in pulling in and the other is better in acceleration, but after all, that is a question of the nature of the load, and also a question as to how much the one advantage or the other is worth under the greater cost of the construction, or whether it is not worth anything at all. It is really like most engineering problems, an economic question between the engineering design and the requirements of service, and the cost of the apparatus; but in the last five or ten years the advantage in development has been largely in improving the starting condition and the fraction synchronous condition, that is, reducing and eliminating the disadvantage of the definite pole construction, so that today the definite pole construction really has practically no disadvantage as a synchronous motor over the uniform reluctance type. Today indeed in the synchronous motor, that field in which there is the least known or available in the literature, are the phenomena of pulling into step, and as you have heard from Mr. Foster a large amount of investigating work is being carried on in this direction, and I hope Mr. Foster will be able, at some of the future meetings, to give us some additional information of the phenomena occurring in the synchronous motor in that range of speed where it is not an induction motor any more, and where it is not yet a synchronous motor.

C. J. Fechheimer (by letter): The many oscillograms in Mr. Newbury's paper convey to our minds an unusually clear picture of the phenomena from standstill to synchronism, of the transients produced by the varying reluctance of the magnetic circuit due to the projecting poles, and those caused by temporary changes when the connections are altered. Inasmuch as the physical conception of a phenomenon frequently is of more importance than the mathematical, especially to the engineer or student who does not design the apparatus, the graphical oscillograph records are of great value.

Mr. Newbury states: " These facts show the desirability of starting synchronous motors with the field circuit closed (and so eliminating the high voltage from the field winding and the switchboard), except in special cases where unusually high initial starting torque is required. For such applications a high resistance damper winding is necessary, the benefits of which in producing torque would be largely nullified by the closed field of circuit. In such special applications, however, care must be taken to insure that the insulation of the entire field circuit will withstand the resulting voltage." This statement applies to motors with rotors equipped with squirrel cage windings and laminated poles. Mr. Newbury has not commented at all on synchronous motors with solid poles. We wish to call attention to the very desirable effects which can be produced

with solid pole rotors in which eddy currents are crowded into thin shells toward the surfaces, (the well-known skin effect phenomenon), whereby the starting torque is increased, whereas the number of inter-linkages of flux with the field turns is reduced, with the result that the induced voltage in the field coils is lowered.

We give below some data from actual solid pole machines which were available for the tests. From them it will be seen that the induced voltage with solid poles is small as compared with that obtained with laminated poles in which the squirrel cage construction is embodied. Instances of these latter are cited in Mr. Newbury's paper. We have taken as a basis of comparison the induced voltage with a torque of 30 per cent of normal full load torque, this value being as large as is usually demanded of synchronous motors at starting.

Rating					D-C. exciting voltage	Rotor voltage for 30% torque
2000-kv-a.	11,000-volt	three-phase	50-cycle	600 rev. per min.	125	1690
180-kv-a.	2300-volt	three-phase	60-cycle	150 rev. per min.	125	1790
350-h. p.	2300-volt	three-phase	60-cycle	257 rev. per min.	250	2610
50-kv-a.	240-volt	three-phase	60-cycle	1200 rev. per min.	125	1440
100-kv-a.	240-volt	two-phase	60-cycle	257 rev. per min.	125	1230
150-kv-a.	275-volt	three-phase	60-cycle	900 rev. per min.	125	427

We do not favor short-circuiting of the field coils at starting, since, for a given starting torque, not only is the line current increased thereby, but there is a possibility of the rotor refusing to accelerate beyond half speed unless the field circuit is opened. As stated by Mr. Newbury, and also in my reply to the discussion of my paper on *Self-Starting Synchronous Motors**, the rheostat resistance is entirely inadequate in assisting toward the reduction of line current for a given torque at the instant of starting. Motors with solid rotors have been built successfully for a number of years, and so far as we are aware, all of them are started with the field circuit open, the induced voltage in no case being prohibitive, no disastrous results having come to our attention as a result of the induced voltage.

It is interesting to note that with the solid pole construction, the torque is not proportional to the second power of the voltage, as is generally assumed, but to a slightly higher power, about 2.1 to 2.5 Similarly, the other quantities vary in a different manner than generally assumed. For example, in a certain 100-kv-a. solid rotor synchronous motor, the following relations were found by plotting results on logarithmic cross-section paper:

1. Torque varied as 2.5 power of voltage.
2. Torque varied as 1.73 power of current.
3. Current varied as 1.38 power of voltage.

*Trans. A. I. E. E., Vol. XXXI, 1912, p. 529.

4. Power input varied as 2.53 power of voltage.
5. Torque varied as 1.05 power of kilovolt-ampere input.
6. Kilowatt input varied as 1.05 power of kilovolt-ampere input.
7. Torque varied as the first power of kilowatt input to rotor.

A comparison of the above relations will reveal their consistency.

We believe that the departures indicated above from what would seem to be the most rational laws are due chiefly to the increased crowding of eddy currents into the shells of the rotor surfaces as the current is increased; thus the reactance of the eddy current paths is reduced, the current is proportionately increased, the power factor is slightly increased, etc. There are advantages in these relations, among them being that they result in a not inconsiderable gain in torque for a given increment of voltage, especially when the demand for such torque is greater than was first anticipated.

At first thought it may appear that the starting characteristics with the solid construction are predicted only with great difficulty due to the uncertainty of the laws which eddy currents follow. We would therefore call attention to the method given in my paper on this subject, and state at this time that we have been using this method for about three years with great success. We have recently modified the method so as to include exponents other than generally assumed, such as indicated above. With these modifications our method is substantially the same as previously described. In fact we believe that greater accuracy in the prediction of starting characteristics can be secured with the solid construction than with the laminated squirrel cage construction, there being less uncertainties in the former than in the latter.

The above is not intended to be more than a partial comparison of solid and laminated pole squirrel cage rotors.

It is now generally conceded, that insofar as the current taken when breaking loose from rest is concerned, the air gap should not be made smaller than would be best suited for the motor after it comes into synchronism and is excited in the ordinary manner. I wish to call attention, however, to my statement given in reply to the discussion of my paper previously referred to: "When operating at synchronous speed without direct-current excitation the current drawn from the line depends almost wholly upon the magnetomotive force required to force the flux across the air gap." From this point of view it will be seen that the effect of the air gap upon line current may be of considerable importance.

In Fig. 7, Mr. Newbury shows that the current after synchronism is less than at any time during acceleration. This would imply that the air gap is small, since as stated above, the air gap reluctance plays the chief part in the current taken after the machine locks into synchronism with no direct-current

excitation. In the various speed-torque curves shown in my paper, the current after locking into synchronism is somewhat greater than just before synchronism is reached. If a synchronous motor is designed to give double torque for pull out and is intended for unity power factor operation, the air gap will generally be of sufficient length to cause the current after locking into step to be greater than at about 95 per cent of synchronism. On the other hand, if the motor is designed with a small air gap and is intended to operate with leading power factor for balancing some of the lagging current in a system, the air gap may be so short that the current flowing when the motor is in synchronism without any direct current excitation is less than at any point during acceleration.

Mr. Newbury starts his synchronous motor on fractional voltage and excites the fields before throwing over to full voltage. He states: "The armature circuit is momentarily opened by throwing from the low voltage to the high voltage and current drops to zero during this interval." If the circuit is to be opened and then closed, his method might be a desirable one in cases where stored energy in the rotating parts is high, frictional torque comparatively small and the mechanical angle between adjacent poles comparatively large, such as would be the case, for example, with synchronous motor-generator sets. On the other hand, were the synchronous motor to drive a reciprocating air compressor, the motor operating at a small angular velocity, the frictional resistance being rather high, the mechanical angle between poles small and the stored energy small, the rotor may change its phase position appreciably during this transitional stage. When full voltage is then applied, there is a possibility of setting up rather high mechanical forces and of causing a momentary large current rush. Hence, we may conceive of trouble ensuing in cases of this kind. It may then be best to throw on full voltage before applying direct-current excitation. If the circuit is kept closed during the transition from fractional to full voltage, we believe it best in all cases to excite the fields on fractional voltage, so as to reduce to a minimum the current which would flow after full voltage is applied.

It is usually undesirable to apply as much as unity power factor exciting current in order to cause the motor to lock into synchronism provided synchronous speed cannot be obtained without the application of such current. In Figs. 11, 12 and 13 and accompanying description in my paper referred to above, it is shown that there is a critical value of excitation for each speed which will give maximum torque, beyond which the torque drops off, but the current in the stator increases. A knowledge of this characteristic may prove valuable to the operator who has had difficulty in causing his motor to lock into synchronism, or finds the current drawn excessive for his supply system.

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STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS

BY H. G. STOTT AND W. S. GORSUCH

The need of some uniform method of accounting for the determination of the cost of power in steam plants has been long felt. The subject, however, seems to have been allowed to drift along without reaching any very definite conclusion, with the natural result that there are numerous forms in use today. These forms are founded upon assumptions which are radically different; for example, some costs are based upon the gross output and others on the net output to feeders, giving results which may vary from 2 to 5 per cent, and yet both may be correct.

This paper is presented with the hope that the Standards Committee may consider the time opportune to adopt a standard method of determining power costs in steam plants using coal, oil or gas for fuel, whereby the various items that enter into the cost of generating electricity can be compared, and at the same time, ascertain whether or not the plant is realizing its full efficiency.

The modern tendency to consolidation of small plants also renders it essential that not only should costs be determined, but that some method should be established whereby the costs in different plants can be corrected to allow for variation in load conditions, cost and quality of fuel, labor, etc.

The subject of this paper is naturally divided into five independent sections, as follows:

I. Production and Production Repairs Costs.
II. Investment Costs.
III. General and Miscellaneous Administration Expenses.
IV. Total Cost of Power.
V. Analysis of Production and Production Repairs Costs and Data.

For the purpose of studying the performance of individual plants, or comparing independent stations, the groups under the first four sections are arranged so that the cost of any item can be determined in cents per kilowatt-hour net output for any period. Section V gives a complete analysis of section I and of the general operating results for the same period.

I. Production and Production Repairs Costs

PRODUCTION COSTS

Group	Cost, cents per kw-hr. net output		
	Labor	Material	Total
P.A. Management and Care			
1. Superintendence			
2. Engineering Staff			
3. Chemists			
4. Clerks			
5. Messengers			
6. Janitors			
7. Watchmen			
8. Store keepers			
9. Elevatormen			
10. Miscellaneous			
Total:			
P.B. Boiler Room			
1. Engineers			
2. Water tenders			
3. Stoker operators			
4. " " assts.			
5. Firemen			
6. Firemen assts.			
7. Feed pumpmen			
8. Oilers			
9. Boiler cleaning			
10. Economizer, cleaning and oiling			
11. Ash handlers			
12. Miscellaneous			
Total:			

PRODUCTION REPAIRS COSTS

Group	Cost, cents per kw-hr. net output		
	Labor	Material	Total
R.A. Furnaces and Boilers			
1. Boilers			
2. Furnace settings (brick)			
3. Stoker and stoker engines or motors			
4. Stoker (parts inside of furnace)			
5. Grate bars			
6. Burners and atomizers			
7. Superheaters			
8. Smoke stacks			
9. Boiler insurance			
10. Miscellaneous			
Total:			
R.B. Boiler Accessories			
1. Economizers			
2. Boiler feed pumps			
3. Heaters			
4. Coal handling apparatus			
5. Ash handling apparatus			
6. Fuel oil handling apparatus			
7. Fuel gas handling apparatus			
8. Miscellaneous			
Total:			

I. Production and Production Repairs Costs—Continued

PRODUCTION COSTS

Group	Cost, cents per kw-hr. net output: Labor	Material	Total
P.C. Engine Room			
1. Engineers			
2. Turbine operators			
3. Wipers			
4. Air pumpmen			
5. Engine oilers			
6. Pump oilers			
7. Miscellaneous			
Total:			
P.D. Electrical			
1. Supt. and operators			
2. Switchboardmen			
3. Dynamo tenders and cleaners			
4. Oil switch attendants			
5. Storage battery attendants			
6. Wiremen			
7. Electrical laboratory			
8. Lighting system			
9. Miscellaneous			
Total:			
P.E. Fuel for Steam			
1. Coal, bituminous, tons (2240 lb.) (1016 kg.)			
2. Coal, anthracite, tons (2240 lb.) (1016 kg.)			
3. Oil			
barrels (hectoliters)			
pounds (kilograms)			
4. Gas, cu. ft. (cu. meters)			
5. Dock rental			
6. Track rental			
7. Miscellaneous			
Total:			
P.F. Water for Steam			
1. Feed water			
2. Condenser water			
3. Chemicals used in purification			
4. Condensing water			
5. Tunnel rental			
6. Miscellaneous			
Total:			

PRODUCTION REPAIRS COSTS

Group	Cost, cents per kw-hr. net output: Labor	Material	Total
R.C. Engines			
1. Reciprocating			
2. L. P. turbines			
3. H. P. turbines			
4. Exciters			
5. Miscellaneous			
Total			
R.D. Engine Accessories			
1. Condensers, barometric and jet			
2. Condensers, surface			
3. Cooling tower			
4. Auxiliary pumps			
5. Miscellaneous			
Total:			
R.E. Piping			
1. Main steam			
2. Auxiliary steam			
3. Exhaust steam			
4. Hot water			
5. Cold water			
6. Blow off			
7. Traps			
8. Oil system			
9. Air system			
10. Miscellaneous			
Total:			
R.F. Electric Generators			
1. Engine driven			
2. Turbine driven, L.P.			
3. Turbine driven, H.P.			
4. Exciters			
5. Miscellaneous			
Total:			

I. Production and Production Repair Costs—Continued

PRODUCTION COSTS

Group	Labor	Material	Total
P.G. Lubricants			
1. All lubricants for machinery			
2. Miscellaneous			
Total:			
P.H. Production Supplies			
1. Rags			
2. Waste			
3. Packing			
4. Fire room tools			
5. Chemical laboratory supplies			
6. Lamps and fuses			
7. Miscellaneous			
Total:			
P.I. Station Expenses			
1. Stationery and printing			
2. House water			
3. Telephone			
4. Miscellaneous			
Total:			
P.J. General			
1. Vehicle service			
2. Personal injuries			
3. Other property damage			
4. Pensions			
5. Miscellaneous			
Total:			

Cost, cents per kw-hr. net output (Labor, Material, Total)

PRODUCTION REPAIRS COSTS

Group	Labor	Material	Total
R.G. Electrical Accessories			
1. Oil switches			
2. Switchboards			
3. Storage battery, exciter			
4. Storage battery, control			
5. Synchronous converters or motor-generators			
6. Signal system			
7. Electrical laboratory			
8. Miscellaneous			
Total:			
R.H. Tools			
1. Machine shop			
2. Repair of all tools			
3. Cranes and hoists			
4. Miscellaneous			
Total:			
R.I. Building			
1. Building			
2. Elevators			
3. Lighting			
4. Heating			
5. Ventilating			
6. Miscellaneous			
Total:			
R.J. General			
1. Vehicle service			
2. Personal injuries			
3. Other property damage			
4. Miscellaneous			
Total:			

Cost, cents per kw-hr. net output (Labor, Material, Total)

Summary of Production and Production Repairs Costs

PRODUCTION COSTS

Group	Labor	Material	Total
P.A. Management and Care			
P.B. Boiler-Room			
P.C. Engine-Room			
P.D. Electrical			
P.E. Fuel for Steam			
P.F. Water for Steam			
P.G. Lubricants			
P.H. Production Supplies			
P.I. Station Expenses			
P.J. General			
Total:			

(Cost, cents per kw-hr. net output)

PRODUCTION REPAIRS COST

Group	Labor	Material	Total
R.A. Furnaces and Boilers			
R.B. Boiler Accessories			
R.C. Engines			
R.D. Engine Accessories			
R.E. Piping			
R.F. Electric Generators			
R.G. Electrical Accessories			
R.H. Tools			
R.I. Building			
R.J. General			
Total:			

(Cost, cents per kw-hr. net output)

	Cost, cents per kw-hr. net output Labor and material
Production......................	
Production Repairs..............	
Total............	

Definitions of Production Groups

The groups are designated by letter and the general items under the groups are numbered for convenience of reference. A miscellaneous item is added to each group to include matters not specifically covered by the general items. When general labor is chargeable to a particular group but not definitely covered by any item of that group, it should be charged to the miscellaneous item.

Group P. A. Management and Care. This includes that portion of the salaries and personal expenses of the station manager or chief engineer, mechanical engineer or superintendent, electrical engineer or superintendent; that portion of the salaries of the engineering staff, chemists and store-keepers chargeable to the generating plant; also salaries of clerks, messengers, janitors, watchmen and elevatormen.

Group P. B. Boiler Room. This covers the cost of all labor in boiler room and elsewhere in the power plant having to do with making steam; including that portion of the salaries of the

assistants to the mechanical engineer or superintendent chargeable to the boiler room; also such labor as water tenders, stoker operators, assistant stoker operators, firemen, assistant firemen, feed pumpmen, oilers, boiler cleaning, economizer cleaning and oiling, ash handlers and miscellaneous.

Coal handlers or coal passers are here called assistant stoker operators or assistant firemen, depending whether the boilers are machine- or hand-fired.

In items 9 and 10 the words " cleaner " and " oiler " are not used, as this work is usually performed by different labor in the boiler room.

GROUP P. C. ENGINE ROOM. This covers the cost of labor on prime movers of all kinds; including that portion of the salaries of the assistants to the mechanical engineer or superintendent that is chargeable to the engine room; also such labor as engineers, turbine operators, wipers, air pumpmen, engine oilers, pump oilers and miscellaneous charges.

GROUP P. D. ELECTRICAL. This covers the cost of all labor in connection with the electric generating apparatus, beginning with the generators driven by the prime movers, and including the switchboard and other auxiliary apparatus up to where the electric current leaves the station; that portion of the salaries of the assistants to the electrical engineer or superintendent that is chargeable to the electric generating apparatus; also such labor as operators, switchboardmen, dynamo tenders, dynamo cleaners, oil switch attendants, storage battery attendants, wiremen and work of the electrical laboratory force chargeable to the station; lighting system and miscellaneous charges.

GROUP P. E. FUEL FOR STEAM. This covers the cost of fuel used under the boilers, for generating steam whether coal, oil or gas, at the cost delivered in the bunkers or tanks; including the cost of fuel and such labor as bucket men, conveyormen, coal hoisters, coal trimmers, trolleymen, weighers and laborers. This also includes dock rental, track rental and any special expenses incurred in disposing of ashes. No portion of the cost of boiler room labor should be charged to this group.

GROUP P. F. WATER FOR STEAM. This covers water for boilers and condensers; tunnel rental for condensing water; also chemicals used in purification. Water for general station purposes is not to be included.

Group P. G. Lubricants. This covers all lubricants for machinery in the generating station, but does not include oil for transformers, or oil for lanterns.

Group P. H. Production Supplies. This covers the cost of all supplies used in the generating plant which are consumed in the operating process, the replacement of which does not constitute a repair or renewal; the cost of repairs of operating tools; also such matters as rags, waste, packing, fire room tools, chemical laboratory supplies, lamps and fuses. Item 7, "Miscellaneous," should include gage glasses, gage washers, gaskets, steam and air hose; bolts, screws, nails, dynamo brushes, etc.

Group P. I. Station Expenses. This covers such matters as stationery and printing; also house water and telephone service. Item 4 "Miscellaneous," includes heating, cleaning systems, fire protection system, janitors' supplies, ice water, toilet service and care of streets, yards, sidings, etc.

Group P. J. General. This covers such general and miscellaneous items that are chargeable to production but not includible in any particular one of the "Production Costs" groups. The vehicle service, whether automobile or horse, can be apportioned between "Production Costs" and "Production Repairs Costs."

Charge to this group all expenditures incident to injuries to persons, and property damaged when caused directly in connection with the production of electric power, as enumerated under the following heads:

(a) *Claim Department Expenses.* This includes salaries and expenses of claim agents, investigators, adjustors, and others engaged in the investigation of accidents and adjustment of claims.

(b) *Medical Expenses.* This includes salaries, fees, and expenses of surgeons and doctors; nursing, hospital attendance, medical and surgical supplies; also other hospital expenses.

(c) *Injuries to Employees.* This includes amounts paid in settlement of claims of employees for injuries arising in the course of their employment; also wages paid to disabled employees while off duty.

(d) *Other Personal Injuries and Property Damage.* This includes amounts paid in settlement of claims of persons other than employees for personal injuries sustained in connection with production of electric power; also amounts paid in settlement of claims for damage to property not owned by the accounting corporation. If the loss is of such character that it is in whole or in part indemnifiable under any contract of insurance carried by the corporation, the indemnifiable portion of the loss shall be credited to items 2 and 3 of Group "P. J."

To this group should also be charged all law expenses in connection with the defense or settlement of damage claims chargeable to the power plant, including:

1. *Salaries and Expenses of Attorneys.* A proper proportion of the salary and expenses of the general solicitor or counsel, and salaries, fees, and expenses of attorneys engaged in this work.
2. *Court Costs and Expenses.* Fees of court stenographers, expenses connected with taking depositions, and other court expenses.
3. *Law Printing.* Cost of law books, and cost of printing briefs, court records, and similar papers.

The above accident, damage and legal expenses are independent of the "General Law Expenses" which are included in Group "A. D.," under the "General and Miscellaneous Administration Expenses."

Item 4 of Group "P. J." covers all pensions paid to retired employees of the power plant, and expenses in connection therewith.

Note: It is important that the expenses of personal injuries, other property damages and pensions, chargeable to the power plant, should be determined independently for the power station, as they are relatively small in comparison with those of some of the other departments. If any difficulty should arise in keeping any of these accounts, they may be estimated as accurately as possible for the purpose of determining the amount chargeable to the power plant.

When any of the operating men under Groups P. B., P. C., P. D., and P. E. are used for repair work, that portion of their time should be charged to the proper groups and items of "Production Repairs."

Definitions of Production Repairs Groups

GROUP R. A. FURNACES AND BOILERS. This covers all the cost in connection with repairing boilers and furnaces. This includes boilers, furnace settings, brick work, bridge walls, arches, jambs, stokers and stoker engines or motors, stoker bars, stoker chains, tuyeres, retorts, grate bars, etc.; damper regulators, tubes, valves, oil atomizers, oil and gas burners in furnace; superheaters and smoke stacks; also boiler insurance and miscellaneous charges.

GROUP R. B. BOILER ACCESSORIES. This covers all fuel handling apparatus and auxiliary apparatus in the boiler room. This includes economizers, boiler feed pumps and primary and secondary heaters; all coal handling machinery such as, tower with foundations, hoisting apparatus, elevators, weighing apparatus, conveyors, crushers, belts, links, brackets, wheels, chutes and gates; all ash handling apparatus such as, cars, conveyors, winches, motors, buckets, chains, wheels, hoppers chutes and gates; also the fuel oil and fuel gas handling apparatus including storage tanks, piping, pumps, heaters filters and meters. The miscellaneous item includes blower engines or motors, injectors and pumps for chemical purification; also water meters, etc.

GROUP R. C. ENGINES. This includes all the cost of repairing prime movers, such as reciprocating engines, low-pressure turbines, high-pressure turbines and steam-driven exciters.

GROUP R. D. ENGINE ACCESSORIES. This covers the cost of repairing accessories to the prime movers, including such matters as barometric condensers, jet condensers, surface condensers, packing tubes, renewing tubes, heads and doors, cooling tower; also air, circulating, vacuum and hot well pumps.

GROUP R. E. PIPING. This covers the cost of repairing the piping system in connection with the making of steam and delivery thereof to the prime movers; including such matters as main steam piping, auxiliary steam, exhaust steam, hot water, cold water, blow off, traps, oil system and air system. House water piping is charged to Group "R. I."

GROUP R. F. ELECTRIC GENERATORS. This includes the cost of repairing engine or turbine driven electric generators; also motor and steam driven exciters.

GROUP R. G. ELECTRICAL ACCESSORIES. This covers the cost of repairing the electrical accessories not included in Group "R. F." This includes oil switches and equipment, switchboards and equipment, such as circuit breakers, switches, instruments, bus-bars, transformers, reactive and resistance coils; also storage batteries for exciter and control with their auxiliary apparatus; synchronous converters, motor-generators, signal system and the expenses of the electrical laboratory force chargeable to "Production Repairs."

GROUP R. H. TOOLS. This covers the cost of repairing station tools and implements that have been capitalized (except fire room tools provided for under Group "P. H."). Among the principal items in this group are blacksmiths', machinists', pipe fitters' tools, pump room tools, engine tools and cutting tools; also cranes, hoists, etc.

GROUP R. I. BUILDING. This covers the cost of repairs of buildings and structures used for power station purposes (except the coal tower which is provided for under Group "R. B."). Item No. 1 "Building" includes the cost of repairs to the building proper, foundations, fixtures therein, maintaining walks, driveways, and ground connected with building. In addition to the building this group should include elevators, lighting (except lamps and fuses); also heating, ventilating, house water piping, etc.

GROUP R. J. GENERAL. This should cover such general and miscellaneous items that are chargeable to "Production Repairs" but not includible in any particular one of the "Production Repairs" groups. The vehicle service whether automobile or horse can be apportioned between "Production" and "Production Repairs."

Personal injuries and other property damage includes all the items mentioned under Group "P. J." providing they are caused directly in connection with "Production Repairs." In cases where the distribution of any of the accounts cannot be definitely determined, apportion them on the basis of one-half to "Production" and one-half to "Production Repairs."

NOTE: Men assigned to the power station such as, foreman

of engine room repairs, machinist foremen, machinists, armature repairers, masons, painters, carpenters, blacksmiths, toolmen, steam fitters, pipe coverers, crane operators, riggers, laborers, etc. are often used for repairs to parts of the system other than the power station. In this case only that portion of the expenses chargeable to the power station should be included in the proper groups and items of " Production Repairs."

II. Investment Costs

That portion of the Total Cost of Power which comes under the heading of " Investment Costs," is for convenience divided into the following groups:

Group		Cost, cents per kw-hr. net output
I. A.	Interest..................	
I. B.	Taxes..........................	
I. C.	Insurance......................	
I. D.	Amortization Fund..............	
I. E.	Miscellaneou...................	
	Total:	

Definitions of Investment Groups

Group I. A. Interest. This covers interest on all capital invested in the power plant including land, buildings and equipment. The amount of interest chargeable to the power plant should be readjusted when necessitated by such changes as additions, betterments, withdrawals, etc.

Group I. B. Taxes. This includes all taxes in connection with and chargeable to the power plant, including land, building and equipment. State franchise tax, revenue tax, etc., should be apportioned on the same basis as the " General and Miscellaneous Administration Expenses," explained under section III. The amount of taxes charged to the power plant should also be readjusted at suitable periods.

Group I. C. Insurance. This covers all fire, casualty, and other insurance that is strictly chargeable to the total operating cost of the power plant. Boiler insurance is included in group " R. K." under " Production Repairs."

Amortization Fund.

Group I. D. In order to define clearly what is meant here by " Amortization Fund " it may be helpful to give a brief

discussion of depreciation to such extent as may be necessary to determine its general relation to the operating costs of steam-driven power plants.

Depreciation may be divided into two general classes: (1) physical depreciation, (2) functional depreciation.

Physical depreciation is the result of deterioration due to wear and tear caused by regular use, decay and the action of the elements. This class of depreciation should be taken care of by maintenance and repairs and everything charged directly to the various groups under "Production Repairs," necessary to keep the plant at 100 per cent efficiency. With this method of keeping accounts the word "depreciation" due to wear and tear, disappears.

Functional depreciation is the result of lack of adaptation to function, caused by obsolescence and inadequacy. Obsolescence is due to changes or advances in the art which renders a piece of apparatus, or a whole class of it, obsolete and uneconomical of use, as compared with new types which have been developed at a later date and which are much more efficient. It is probable that an expensive machine which is in good working order may become obsolete and require replacement well within its expectation of life.

Inadequacy results from changed conditions, growth or decline of business, rendering the apparatus or property inadequate for its purpose, and necessitating the installation of machinery capable of better meeting the requirements.

This class of depreciation cannot be prevented by maintenance, or offset by repairs, but can only be taken care of by complete replacement, and should therefore be provided for by means of a renewal, reserve fund or "Amortization Fund", the term by which it is designated in this paper. With the "Amortization Fund" an arbitrary percentage should be set aside and that percentage corrected, if necessary periodically, so that when the apparatus is condemned on account of obsolescence or inadequacy, there will be a fund which will meet the expenses.

It is a difficult matter to predict in advance the length of time that a piece of apparatus or an entire plant may remain in good serviceable condition before it becomes ineffective, and for this reason the amount originally estimated to be set aside periodically should be taken up for revision, say, every five or ten years, and an adjustment should be made by increasing or diminishing the allowance as the circumstances may require.

The amount estimated to be set aside is to be charged to operating expenses as covered by group " I. D." (Amortization Fund) under " Investment Costs," and the money so charged to be taken and invested at compound interest so that the accumulated amount will equal the original cost less scrap value at the end of the assumed life. Under the " Amortization Fund " method the existing fund is always less than it would be under the straight line method.

There are two ways in which the " Amortization Fund " can be invested: first, in securities with a regular market value and thus saleable at any time and in which case there would be a nominal rate of interest; second, this fund can be invested in the company's own business, provided it be left in such a way as will render it readily available when needed; in this case a higher rate of interest may be expected. The objection to the first scheme is that the company borrows money at a high rate of interest and loans it at a low rate of interest. However, it is not within the scope of this paper to discuss the nature of investment, but to recommend that a fund be provided to cover the expenses when it is necessary to scrap old apparatus and replace with new.

The expense of all replacements or renewals which do not have any substantial increase in capacity over the equipment or apparatus for which they were substituted, is to be covered by the " Amortization Fund." Where a substitute has a substantially greater capacity than that for which it is substituted, the cost of substitution of one of the same capacity as the apparatus replaced should be taken care of by the " Amortization Fund," and the remaining portion of the cost of the actual substitute should be charged to capital account.

To establish the amount to be set aside annually for apparatus or power plant, it will be necessary first, to determine the original cost, scrap value, estimated life and rate of interest to be received.

Cost of Apparatus or Power Plant. Where the " Amortization Fund " is started at the beginning of the plant's service, the original cost less the estimated scrap value should be used as the basis upon which to determine the rate. Where the account is not started for some years after the plant is put into operation, the value used should be the original cost less scrap value less the amount that would be existing in the invested

fund at that time if there had been an "Amortization Fund" started at the beginning of the plant's service.

Scrap Value. By scrap value is meant the fair market price of old apparatus after deducting the cost of removal. It is a difficult matter to anticipate just what the scrap value will be as with nearly all equipment, it depends upon its condition when it becomes obsolete or inadequate. If the apparatus is still serviceable a higher price than scrap value may be obtainable, and its worth in this case is characterized as "Salvage Value." For the purpose of determining the amortization fund rate, we will consider only the scrap value and assume the approximate values in percentage of the original cost as indicated in the Life Expectancy Table that follows.

Estimated Life of Apparatus. How long apparatus or equipment will remain in service before it becomes obsolete, inadequate or ineffective, is purely a speculative matter. Past experience, knowledge of the art and careful judgment are the only factors available for arriving at the probable life of apparatus and property. For this reason the Amortization Fund rate should be adjusted periodically as the life of some apparatus may be longer and some shorter than anticipated.

The following "Life Expectancy Table" we believe gives fairly representative figures of what may be expected in first-class steam-driven power plants of to-day.

TABLE I—LIFE EXPECTANCY TABLE

Property	Total life (years)	Scrap value, per cent of original cost
Buildings	75	5
Boilers, stokers and furnaces	20	5
Conveyers, elevators and hoists	20	1
Turbines, complete	12	10
Engines and condensers	12	10
Piping, values and traps	12	3
Pumps	12	5
Synchronous converters, transformers and exciters, etc.	20	10
Switching apparatus and instruments	12	5
Alternators	12	10
Motors	20	10
Tools and sundries	10	3
Storage batteries	10	10

Interest on Invested Fund. The rate of interest that will be received on the money set aside for renewals under the "Amorti-

zation Fund" will depend upon where and how the fund is invested.

The following illustration will demonstrate how the amount to be set aside annually at compound interest for the "Amortization Fund" can be determined for a new Steam-Driven Turbine Power Plant costing $75 per kilowatt economical rating including the building and equipment complete. Land generally appreciates and therefore is not considered in this illustration.

The first operation will be to ascertain the original cost of each principal item as given in the "Life Expectancy Table", the sum of which must be equal to the total original cost of the plant, and then deduct the scrap value to obtain the cost on which to base the "Amortization Fund." The annual amount to be charged to the "Amortization Fund" for each item and to be set aside at 4 per cent compound interest which will accumulate a sum equal to the original cost less the scrap value at the end of the expected life, can be computed from standard annuity tables.

The costs per kilowatt economical rating of the various elements entering into the power plant as given in Table II, are only approximate for steam turbine plants having a capacity of 25,000 kw. or more.

TABLE II

Property	Original cost per kilowatt economic rating	Total original cost of 25,000-kilowatt plant	Total original cost less scrap value of 25,000-kilowatt plant	Annual charge to "Amortization Fund"
Building	$20.00	$500,000	$475,000	$1,059
Boilers, stokers and furnaces	21.00	525,000	498,750	16,750
Conveyors, elevators and hoists	4.50	112,500	111,375	3,741
Turbines, complete	10.00	250,000	225,000	14,970
Condensers	4.25	106,250	95,625	6,408
Piping, valves and traps	4.50	112,500	109,125	7,265
Pumps	0.75	18,750	17,813	1,186
Synchronous converters, transformers, exciters, etc.	3.00	75,000	67,500	2,268.
Switchboard apparatus and instruments	3.80	95,000	90,250	6,006
Motors	0.20	5,000	4,500	151
Tools and sundries	3.00	75,000	72,125	5,938
	$75.00	$1,875,000	$1,748,188	$65,742

It will be seen from Table II that when the scrap value is deducted $1,748,188 or 93.2 per cent of the original cost of the plant including building and complete equipment, remains to be covered by the "Amortization Fund;" 27.2 per cent of the $1,748,188 represents the building and 72.8 per cent the equipment.

The amount to be set aside annually is, $1,059 for the building and $64,683 for the equipment or $65,742 for the entire plant, which is equivalent to 0.223 per cent of the total original cost of the building less scrap value and 5.08 per cent of the total original cost of the equipment less scrap value or 3.76 per cent of the total original cost of building and equipment less scrap values respectively.

In case an "Amortization Fund" has not been maintained at all for a large part of the plants' life and it is desired to provide for a portion of the equipment and building during the remaining life, the operation will be the same as described above with the exception that it will be necessary to determine the value as stated under the heading "Cost of Apparatus or Power Plant," and estimate the remaining life.

The average weighted life of the equipment complete, considered as a whole, is obtained by multiplying the assumed life in years of each item by the cost of the item and dividing the sum by the total cost of all the equipment. The average weighted life in this illustration is approximately 16 years.

Readjustment of Amortization Fund. The percentage or amount that is annually set aside for the "Amortization Fund" should be periodically readjusted to correct for the possible change in assumed life, increase or decrease in cost due to additions, replacements or renewals and withdrawals.

If after a plant has been in operation for five years it is found that the estimated life of certain portions of the equipment is longer and other portions shorter than was anticipated, the "Amortization Fund" can be readjusted as follows:

Establish a new "Life Expectancy Table" and obtain the remaining life of each item upon which the revised annual charge is to be based. Determine the cost of each item for calculating the revised percentage to be set aside, by deducting from the "Total Original Cost Less Scrap Value" given in Table II, the amount of the "Amortization Fund" at the end of 5 years plus the compound interest on this amount at 4 per cent for a period equal to the remaining life. The

" Revised Annual Charge to the Amortization Fund " can be then computed from annuity tables as in the previous illustration.

TABLE III—LIFE EXPECTANCY TABLE

Property	Estimated total life in years		Revised remaining life after 5 years
	Original	Revised	
Building	75	75	70
Boilers, stokers and furnaces	20	18	13
Conveyors, elevators and hoists	20	15	10
Turbines, complete	12	10	5
Condensers	12	10	5
Piping, valves and traps	12	10	5
Pumps	12	10	5
Synchronous converters, transformers, exciters, etc.	20	22	17
Switchboard apparatus and instruments	12	14	9
Motors	20	15	10
Tools and sundries	10	12	7

The average weighted life of the equipment taken as a whole on the basis of the revised " Life Expectancy Table " is 14.5 years, whereas with the originally estimated life it is 16 years.

TABLE IV

Property	Total original cost less scrap value of 25,000 kilowatt plant	Original cost less scrap value, A. F. amount for 5 years. and interest of amount for remaining life	Revised annual charge to Amortization Fund
Building	$475,000	$385,663	$1,059
Boilers, stokers and furnaces	498,750	347,750	20,915
Conveyors, elevators and hoists	111,375	81,385	6,782
Turbines, complete	225,000	126,340	23,320
Condensers	95,625	53,410	9,870
Piping, valves and traps	109,125	61,275	11,320
Pumps	17,813	10,002	1,847
Synchronous converters, transformers, Exciters, etc.	67,500	43,580	1,839
Switchboard apparatus and instrument	90,250	43,930	4,150
Motors	4,500	3,289	274
Tools and sundries	71,250	28,910	3,660
	$1,748,188	$1,185,534	$85,033

From the above table it will be seen that the amount to be set aside annually is $1,059 for the building and $83,977 for the equipment or $85,036 for the entire plant. The percentage that is to be set aside after 5 years is 4.86 per cent of the total original cost of the building and equipment less scrap value, which is an increase of approximately 29.5 per cent over that originally estimated.

In a similar way the "Amortization Fund" should be readjusted when additional equipment is installed, old apparatus renewed, replaced or withdrawn.

GROUP I. E. MISCELLANEOUS. Charge to this group that portion of other investment costs chargeable to the "Total Cost of Power" and not specifically covered by any of the above groups.

Annual expenses of franchises and other intangible capital not specifically a departmental charge is to be apportioned as explained in Section III, "General and Miscellaneous Administration Expenses."

III. GENERAL AND MISCELLANEOUS ADMINISTRATION EXPENSES.

The "General and Miscellaneous Administration Expenses" are chargeable to all departments and to make an equitable distribution of these expenses it is proposed to deduct the charges that are clearly departmental charges, such as, boiler insurance, casualty insurance, other insurance, personal injuries, damage to other property, pensions etc., and to apportion the remainder on the basis of the percentage of the departmental costs (exclusive of the General and Miscellaneous Administration Expenses and Investment Costs) to the total "Running Expenses" of the corporation.

For illustration, the portion of "General and Miscellaneous Administration Expenses" chargeable to the power plant in percentage, is,

$$\frac{\text{Total production costs plus total production repairs costs}}{\text{Total running expenses of the corporation}} \times 100$$

After this percentage is determined, the amounts chargeable to the power plant and covered by the groups under "General and Miscellaneous Administration Expenses," can be obtained and the cost per kw-hr. net output calculated.

GENERAL AND MISCELLANEOUS ADMINISTRATION EXPENSES.

Group		Cost, cents per kw-hr. net output
A. A.	Salaries and Expenses of General Officers....................	
A. B.	Salaries and Expenses of General Office Clerks................	
A. C.	General Office Supplies and Expenses...................	
A. D.	General Law Expense...........	
A. E.	Relief Department..............	
A. F.	General Stationery and Printing..	
A. G.	Store Expenses.................	
A. H.	Miscellaneous General Expenses..	
	Total:	

Definitions of General and Miscellaneous Administration Groups

GROUP A. A. SALARIES AND EXPENSES OF GENERAL OFFICERS. This includes the salaries, traveling and incidental expenses of the directors, president, vice-president, treasurer, secretary, comptroller, general auditor, general manager, assistant general manager, chief engineer, general superintendent, purchasing agent, and all other officers whose jurisdiction extends to the entire system and whose services cannot be satisfactorily allocated to the several departments.

GROUP A. B. SALARIES AND EXPENSES OF GENERAL OFFICE CLERKS. This includes the salaries and traveling and incidental expenses of general office auditors, bookkeepers, cashiers, paymasters, stenographers, clerks employed in counting cash, and all other clerks employed in the general office.

Salaries and expenses of clerks in the commercial department are not to be charged to this group.

GROUP A. C. GENERAL OFFICE SUPPLIES AND EXPENSES. This covers the cost of office supplies, repairs of office furniture, and renewals of such furniture as has not been capitalized; wages of janitors, porters, and messengers; rent of rooms in office buildings, repairs of such rented rooms, and all other miscellaneous expenses of general offices. Office expenses of departmental officers must be charged to the proper departmental accounts.

GROUP A. D. GENERAL LAW EXPENSES. This covers all law expenses except those incurred in the defense and settlement of damage claims, chargeable to the power plant and

covered by Groups "P. J." and "R. T." and those chargeable to other departments. This includes salaries and expenses of all counsel, solicitors and attorneys, their clerks and attendants, and expenses of their offices; cost of law books, printing briefs, legal forms, testimony, reports, etc.; fees and retainers for services of attorneys not regular employees; court costs and payments of special, notarial and witness fees not provided for elsewhere; expenses connected with taking depositions and all law and court expenses not provided for elsewhere.

Group A. E. Relief Department. This covers all salaries and expenses incurred in connection with conducting a relief department; also contributions made to such department.

Note. All pensions paid to retired employees, and expenses in connection therewith are charged directly to the department and in case of the power plant, it is covered by item 4 under Group "P. J." of "Production Costs."

Group A. F. General Stationery and Printing. This includes all expenses for stationery and printing, stationery supplies and postage except as hereinafter provided:

The cost of printing briefs and other legal papers shall be charged to Group "A. D.," "General Law Expenses," or Groups "P. J." and "R. T." in accordance with the purpose of the printing.

The cost of printing signs, posters, and other advertising matter shall not be charged to this group, as no portion of such expenses are chargeable to the power plant.

The cost of such mechanical calculators, typewriters, duplicating machines and other office appliances as are not properly capitalized, shall, if for use in general offices, be charged to Group "A. C.," "General Office Supplies and Expenses." If these appliances are for use of departmental offices, they should not be charged to this group, but to departmental accounts.

Group A. G. Store Expenses. Charge to this group all salaries and expenses in connection with store-rooms, including cost of sending material and supplies from general store-rooms to branch store-rooms, and the collection of scrap material.

Group A. H. Miscellaneous General Expenses. This covers the cost of telephone service, telegrams, and all other miscellaneous expenses not specifically covered by any one of the "General and Miscellaneous Administration Expenses" groups.

IV. Total Cost of Power

The total cost of power as covered by this section is conveniently divided into two distinct parts and includes all the costs chargeable to the power plant and that have to do with the production of power, but does not include any portion of the transmission, distribution, utilization or commercial expenses. First, for comparative purposes and for a study of plant economics the total cost of power should consist of production costs plus production repairs costs plus investment costs. Second, for the purpose of exchanging or selling power or for a study of independent plants with a view of combination, the total cost of power should include production costs plus production repairs costs plus investment costs plus General and Miscellaneous Administration Expenses.

Sections	Costs, cents per kw-hr. net output
I. Production Cost.................	
I. Production Repairs Cost..........	
II. Investment Cost.................	
Total Cost of Sections I and II.	
III. General and Miscellaneous Administration Expenses...........	
Total Cost of Sections I, II, and III	

V. Analysis of Production and Production Repairs Costs and Data

Item

1. Cost of Production plus Production Repairs in cents per kw-hr. net output...
2. Percentage of fuel cost to the cost of Production plus Production Repairs....
3. Percentage of labor cost of Production and Production Repairs to total cost of Production and Production Repairs................................
4. Percentage of fuel cost to labor cost of Production and Production Repairs..
5. Percentage of cost of Production and Production Repairs used for repair materials, supplies etc. (100—items 2 and 3)........................
6. Percentage of total Production cost to total cost of Production and Production Pepairs..
7. Percentage of total cost of Production Repairs to total cost of Production and Production Repairs...
8. Percentage of total cost of Production Repairs to total cost of Production...
9. Average daily wages per man...
10. Kilowatt hours net output per man..................................
11. Cost of feed water per 1000 cubic feet (28.32 cubic meters)...............
12. Boiler feed water purchased per kw-hr. net output, pounds (kilograms)......
13. Cost of handling coal per ton (2240 lb.) (1016 kg.)......................

14. Average cost
- Coal per ton (2240 lb.) (1016 kg.)
- Fuel oil per barrel (42 U. S. gallons (1.59 hectoliters)....
- Fuel gas per 1000 cubic feet (28.32 cu. meters)

15. Average B.t.u. (large calories)
- Coal per lb. (0.4534 kg.) (moist, as received)
- Fuel oil per pound (0.4534 kg.)...........
- Fuel gas per cubic foot (0.028 cu. meter)

16. Average B.t.u. (large calories) per dollar
- Coal
- Fuel oil........................
- Fuel gas.

17. B.t.u. (large calories) supplied per kw-hr. net output
- Coal
- Fuel oil.............
- Fuel gas

18. Coal factor = coal per kw-hr. net output (pounds) (kilograms).............
19. Fuel oil per kw-hr. net output (pounds) (kilograms).......................
20. Fuel gas per kw-hr. net output (cubic feet) (cu. meters)..................
21. Kw-hr. net output
- Coal per ton (2240 lb.) (1016 kg.)
- Fuel oil per barrel (42 U. S. gallons) (1.59 hectoliters)
- Fuel gas per (1000 cu. ft.) (28.32 cu. meters)

22. Kind and size of coal..
23. Kind of fuel oil and sp. gr...
24. Kind of fuel gas..
25. Average percentage of ash in coal as received...........................
26. Average B.t.u. (large calories) per pound (0.4534 kg.) of refuse from coal....
27. Net thermal efficiency of plant in per cent

$$= \frac{\text{Total kilowatt hours net output} \times 3415}{\text{Average B.t.u. per ton} \times \text{tons of coal used}} \times 100$$

28. Load factor of load...

29. Figure of merit (for coal)

$$= \frac{\text{B.t.u. per ton (Moist)} - \left(\frac{2240 \times \%\ \text{ash}}{100} \times \text{B.t.u. per pound of refuse}\right)}{\text{Price per ton (2240 lb.) (\$)}}$$

$$= \frac{\text{Large calories per 1016 kg.} - \left(\frac{1016\ \text{kg.} \times \%\ \text{ash}}{100} \times \text{large calories per kg. of refuse}\right)}{\text{Price per 1016 kg. (\$)}}$$

Discussion of Analysis of Production and Production Repairs Costs and Data

ITEM 1. This figure is determined by dividing the total Production and Production Repairs costs by the total kilowatt-hours net output for the period. By net output is meant the power that leaves the generating station for distribution. The total cost of Production and Production Repairs per kilowatt-hour as obtained from summary under Section I, will give the same result.

ITEM 2. This figure is obtained by dividing the total cost of fuel by the total cost of Production and Production Repairs

and multiplying by 100, or by dividing the cost of material only in Group "P. E.," by the cost of Production plus Production Repairs per kilowatt-hour as obtained from the summary under Section I and multiplying by 100.

ITEM 3. Divide the total cost of labor of Production and Production Repairs by the total cost of Production and Production Repairs and multiply by 100, or divide the cost of labor per kilowatt-hour in all the groups by the total cost per kilowatt-hour given in the summary of Section I and multiply by 100.

ITEM 4. Divide the total cost of fuel by the total cost of labor of Production and Production Repairs and multiply by 100, or divide the cost of material only, in Group "P. E.," by the total cost of labor per kilowatt-hour in all the groups as obtained from summary of Section I, and multiply by 100.

ITEM 5. Determine this figure by subtracting the percentages obtained in Items 2 and 3 from 100.

ITEM 6. Divide the total cost of Production by the total cost of Production and Production Repairs and multiply by 100, or divide the total cost of Production per kilowatt-hour by the total cost of Production and Production Repairs per kilowatt-hour and multiply by 100.

ITEM 7. Obtain this figure by dividing the total cost of Production Repairs by the total cost of Production and Production Repairs and multiplying by 100, or divide the total cost of Production Repairs per kilowatt-hour by the total cost of Production and Production Repairs per kilowatt-hour and multiply by 100.

ITEM. 8. Divide the total cost of Production Repairs by the total cost of Production and multiply by 100, or divide the total cost of Production Repairs per kilowatt-hour by the total cost of Production per kilowatt-hour and multiply by 100.

ITEM 9. Obtain this figure by dividing the total daily cost of all labor by the total number of men included in all the "Production" and "Production Repair" groups with the exception of Group "P. A." The "Average Daily Wages per Man" is materially affected by local conditions and this should be taken into consideration when comparing power costs. The "Reduction Factor" to be used in this case is the ratio of the lower to the higher "Average Daily Wages per Man."

To compare the cost per kilowatt hour net output of two independent plants on the same basis, apply the "Reduction Factor" to labor only of all groups with the exception of Group "P. A." and add or subtract the difference to or from the total cost of "Production" plus "Production Repairs" per kilowatt hour net output.

Group "P. A." "Management and Care," is practically independent of load conditions and labor unions and is therefore not considered in applying the "Reduction Factor" for labor.

ITEM 10. This figure is obtained on the basis of all men included in the Production and Production Repairs groups with the exception of Group "P. A." The kilowatt hours per man increase as the station becomes larger in size, and consequently the cost of labor per unit generated becomes less.

ITEM 11. This figure is determined by dividing the total cost of feed water delivered by the number of 1000 cubic feet (28.32 cu. meters) received. If there is any additional pumping charge, it should be included in the cost of water.

ITEM 12. This figure can be determined by dividing the water purchased by meter for the boilers by the total kilowatt hours net output.

ITEM 13. Divide the total cost of labor as covered by Group "P. E." items 1 and 2 by the total number of tons of coal handled. The cost of labor for coal handling apparatus in Group "R. B." item 4 is not to be included.

ITEM 14. These figures are to be determined on the basis of what was actually paid for the fuel.

ITEM 15. The calorific values of coal and fuel oil should be determined by the bomb type calorimeter in which the combustible is burned in the presence of oxygen under pressure, as this is the most accurate and satisfactory device for solid fuels. The gaseous fuels should be tested in a recognized standard calorimeter equivalent to the Junker.

ITEM 16. Determine these figures by dividing the total B.t.u. (large calories) in fuel as received, by the actual cost of the fuel.

ITEM 17. Determine these figures by dividing the total B.t.u. (large calories) contained in the fuel, by the total kilowatt hours net output for the period. The total B.t.u. (large calories) contained in the fuel is equal to the B.t.u. (large calories) obtained

from proximate analysis, multiplied by the total number of pounds (0.4534 kg.) of coal, oil or cubic feet (0.028 cu. meter) of gas used.

ITEM 18. Divide the total number of pounds (kilograms) of coal used by the total kilowatt-hours net output.

ITEM 19. Divide the total number of pounds (kilograms) of fuel oil used by the total kilowatt-hours net output.

ITEM 20. Divide the total number of cubic feet (cu. meters) of gas used by the total kilowatt-hours net output.

ITEM 21. These figures can be obtained by dividing the total kilowatt-hours net output by the total amount of fuel used. One barrel equals 42 U. S. gallons or 1.59 hectoliters.

ITEM 22. State whether, anthracite, semi-anthracite, bituminous, semi-bitumious also if pea, No. 1, No. 2 or No. 3 buckwheat or rice coal, etc.

ITEM 23. State if crude or distilled or reduced fuel oil. The average heating value per pound of crude oil generally increases as the specific gravity diminishes, but the specific gravity of an oil is not an accurate index of its calorific value. However, it may be of interest for comparison to give the specific gravity under this item.

ITEM 24. State whether natural gas, coal gas or producer-gas, etc.

ITEM 25. This is determined by the usual proximate analysis which is made when the coal is received.

ITEM 26. This is determined by making a series of tests during the period on the refuse taken from the ash heap, sampled and analyzed in the same manner as the coal in Item 15.

ITEM 27. The net thermal efficiency of a steam-driven power plant in per cent is

$$\frac{\text{Total kilowatt-hours net output} \times 3415}{\text{Average B.t.u. per ton} \times \text{tons of coal used}} \times 100$$

Average B.t.u. per ton (moist, as received) is obtained by multiplying item 15 by 2240.

The net thermal efficiency is the true measure of the scientific perfection of the design of plant, whereas the cost per kilowatt-hour is the true engineering criterion of the perfection in efficiency of the plant.

Relation Between Load Factor and Costs

ITEM 28. The term "load factor" has been used in so many different ways, that much confusion still exists among a number of central station men. In some instances maximum station capacity, machine rating and connected load when considering a motor load are used, instead of actual maximum load. Load factor based upon the rated capacity shows a wide amount of variation, but when based upon the actual maximum load upon the plant during the period, it is considerably more uniform. If load factor figures are to be of any value for comparative purposes, they must be on a uniform basis, using the total number of hours in the period under consideration.

Load factor, as used in this case, is load factor of the load for any period and is defined as the ratio of actual net output during the period, to the net maximum hour's load multiplied by the total hours in the period. Thus daily load factor of load in per

$$\text{cent} = \frac{\text{Actual net output for day of 24 hours}}{\text{Net maximum hour's load} \times 24} \times 100.$$ For the

purpose of comparing any two plants for a given period the load factor of the load on the basis of the maximum hour during the period should be used and not the average of daily load factors. The monthly load factor of load is usually much lower than the average of daily load factors. In railway service the peaks on Saturdays, Sundays and holidays are comparatively small and consequently the load factor is relatively higher than on other days. In lighting stations the load factor is usually higher on Saturdays and holidays and lower on Sundays than on other days.

Load factor has an important effect on the cost of producing power. A low load factor involves the use of relatively large equipment operating at light and inefficient loads, but with a high load factor, all the elements that enter into the production of power are operating at maximum economy, and the cost of power is at a minimum. In any given system using coal as fuel, with approximately the same average maximum hour load the following relative changes take place with a change in load factor, providing the load factor remains changed over a reasonably long period of say at least six months.

The total cost of management and care is practically constant and independent of the load factor, but the cost per kilowatt-

hour net output increases as the load factor decreases. To a certain extent the cost of labor varies with the load factor, but at about 25 per cent load factor the number of men required to operate the plant seems to reach a minimum, and below this point, it practically remains constant. The total cost of water, lubricants, supplies and most of the repairs, varies almost directly with the load factor, as the costs of these individual items are practically functions of machine hours. The total cost of coal varies with the load factor but not quite so rapidly, whereas the cost of coal per kilowatt-hour net output increases with a decreasing load factor. The total kilowatt-hour net output, turbine, engine and active fire hours vary directly with the load factor. The banked fire hours increase with a decrease in load factor but not quite so rapidly. The reserve fire hours slightly increase with a decrease in load factor.

It has been found that the relationship between load factor and cost of production plus production repairs in a first-class steam plant using coal as fuel, is that the cost per kilowatt-hour net output varies approximately as the inverse fourth root of the load factor. This law will hold between 15 per cent and 90 per cent load factors and is applicable to individual plants, but in comparing independent plants the cost of power in each plant should be reduced to a common load factor.

Fig. 1 illustrates graphically the relation between the cost of power and load factor for steam turbine plants of 25,000 kilowatts capacity and larger, using coal costing \$3.00 per ton, having 14,500 B.t.u. per pound or approximately 10,840,000 B.t.u. per dollar. The investment costs are shown by the curves above and the cost of producing power by the curves below the axis, so that the sum of the ordinates gives the total cost per kilowatt-hour net output for any load factor.

The full line curves are for a steam turbine plant operating at normal rating which is here considered to be the economical rating of the prime mover. The cost of equipment and building is taken at \$75 and the land at \$6 per kilowatt economical rating. The dotted lines show the charges for a plant operating at the maximum two-hour overload rating of the prime mover. In this case the cost of equipment and building is reduced to \$60 and the land to \$4.8 per kilowatt maximum two-hour overload rating. In each case 5 per cent is allowed for interest, 1 per cent for taxes, 1 per cent for insurance and 3.5 per cent for amortization fund, making a total investment charge of 10.5 per cent.

It is readily seen from the curves that the most important item entering into the cost of production and production repairs is that of fuel, and during the greater part of the day when the load is relatively light the investment costs unquestionably have

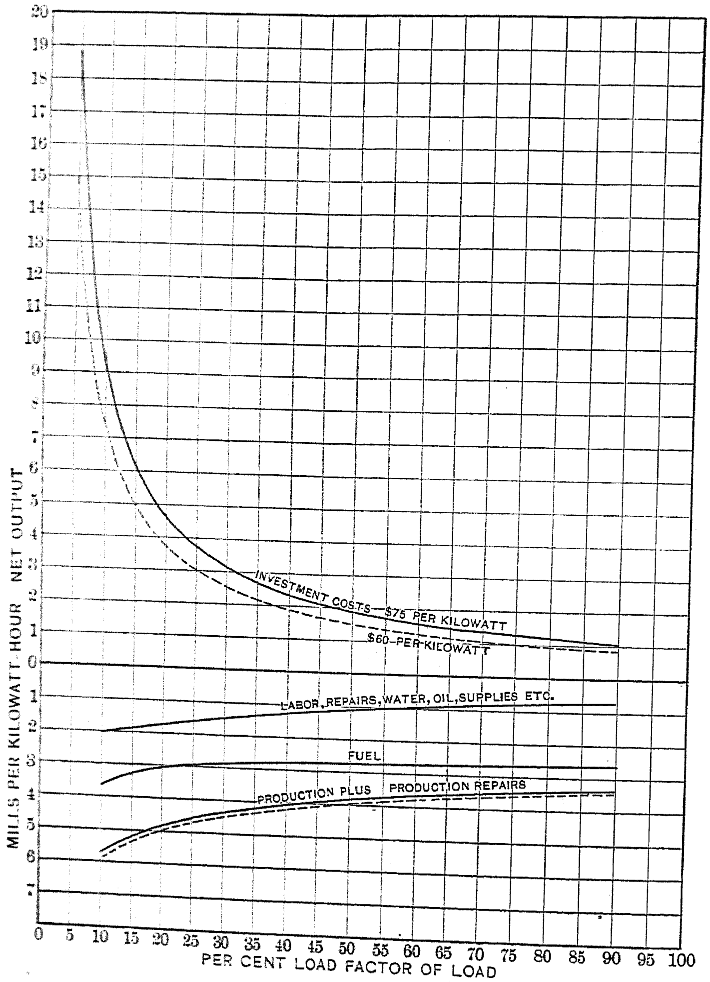


FIG. 1

the greatest influence on the total cost of power. At 20 per cent load factor the investment costs are approximately equal to the production plus production repairs costs for the $75 plant, and become much higher as the load factor decreases. The total

yearly investment costs is dependent upon the rated capacity but independent of the output.

The lower dotted curve shows the cost of production plus production repairs during the maximum hour periods when operating at maximum overload rating or 25 per cent above economical rating. This is approximately 2.25 per cent higher than the cost for economic operation. During the other periods the cost will be the same as when operating at normal rating or maximum economy.

If at any load factor the two ordinates are added it will be found that the total cost of power is less when operating at overload rating notwithstanding the increase in cost due to poor economy at overload. This shows the marked influence of the investment costs on the total cost of power. In other words with sufficient margin for insurance the plant can be run at the maximum overload capacity during the maximum hour periods at the sacrifice of a large percentage in efficiency during these periods.

The investment cost curve is obtained by dividing a constant by a variable and consequently it is an equilateral hyperbola. The equation of this curve referred to its asymptotes as co-ordinates which are at right angles is

$$Y_{\text{I}} = \frac{x\ y_i}{X} \tag{1}$$

in which Y_{I} represents the investment cost in mills per kilowatt-hour net output, X the corresponding load factor of load expressed in per cent and $x\,y_i$ a constant for any given curve, where x and y_i are the co-ordinates of any point on the curve. To compute the investment costs of any plant for any load factor it will be necessary first to determine the value of $x\,y_i$ in which x represents the present load factor and y_i the corresponding investment cost.

The curve showing the cost of production plus production repairs per kilowatt net output is an inverse fourth root curve and is represented by the equation

$$Y_{\text{P}} = \frac{y_p \sqrt[4]{x}}{\sqrt[4]{X}} \tag{2}$$

in which Y_{P} represents the cost in mills per kilowatt-hour net output, X the corresponding load factor of load in per cent and $y_p \sqrt[4]{x}$ a constant for any given curve, where x and y_p

are the co-ordinates of any point on the curve. To compute the production plus the production costs of any station for any load factor, first determine the value of $y_p \sqrt[4]{x}$, where x is the present load factor and y_p the corresponding cost.

Illustration: If a plant is operating at 30 per cent load factor with a cost of 4.4 mills for production plus production repairs and 3.1 mills for investment, making a total cost of 7.5 mills per kilowatt net output, what will be the cost if the plant were operated at 50 per cent load factor?

Investment Cost

$$Y_I = \frac{30 \times 3.1}{50} = 1.86 \text{ mills}$$

Production plus Production Repairs Costs

$$Y_P = \frac{4.4 \sqrt[4]{30}}{\sqrt[4]{50}} = 3.87 \text{ mills}$$

Total cost of power per kilowatt
net output..................5.73 mills

If it is desired to obtain the total cost of power including the "General and Miscellaneous Administration Expenses," it will be necessary to determine the cost in mills per kilowatt net output of Groups "A.A." to "A.H." as discussed under section III when operating at 30 per cent load factor, substitute in equation (1), solve for Y and add the result to the above figures 5.73 mills.

Figure of Merit and Reduction Factor for Determining Relative Value of Coals

ITEM 29. The item of fuel has such an important influence on the cost of producing power, that in order to compare the economy of operation of different plants it is necessary to know the character and cost of coal used in each case. In order to establish an equitable basis upon which one coal can be compared with another of different price and from a different locality, the term "Figure of Merit" is proposed, which represents the B.t.u. per dollar after correcting for ash, and B.t.u. lost in refuse as follows:

Figure of merit

$$= \frac{\text{B.t.u. per ton (moist)} - \left(\dfrac{2240 \times \%\text{ ash}}{100} \times \text{B.t.u. per pound of refuse}\right)}{\text{Price per ton, (2240 lb.) (\$)}}$$

The B.t.u. per ton (moist, as received), is obtained by multiplying item No. 15 by 2240. Percentage of ash in coal as received and the B.t.u. in refuse from the coal are obtained from items 25 and 26. The price per ton of coal (2240 lb.) is the actual price paid the contractor. For illustration take two coals, " A " and " B ":

Coal	B.t.u. per pound moist	Price per ton (2240 lb.)	Percentage of ash in coal as received	B.t.u. per pound refuse	Figure of merit
A	14,500	$3.00	5	3,500	10,696,000
B	13,000	2.00	10	4,000	14,112,000

The " Figure of Merit " of coal " B " is approximately 32 per cent higher than that of coal " A."

For the purpose of comparing the production costs per kilowatt-hour on a common basis, using fuel having the same " Figure of Merit," it will be necessary to adopt a " Reduction Factor " for correcting the cost of coal having the lowest " Figure of Merit," " Reduction Factor," being defined as the ratio of the lower to the higher " Figure of Merit." In the above illustration the " Reduction Factor " is

$$\frac{\text{Figure of merit coal ``A''}}{\text{Figure of merit coal ``B''}} = \frac{10{,}696{,}000}{14{,}112{,}000} = 0.758$$

Applying this factor to coal " A " is equivalent to saying that in order to compare coals " A " and " B " on the same basis, with respect to B.t.u., percentage of ash in the coal, B.t.u. in the refuse and the price per ton, coal " A " should cost $2.27 per ton instead of $3.00. If it is desired to compare the costs per kilowatt-hour net output on the same basis, one using coal " A " and the other coal " B," apply the " Reduction Factor " to cost of fuel (material only) in group " P. E." items 1 and 2 of plant using coal " A " and subtract the difference from the total cost of " Production " per kw-hr. net output.

Application of Factors

In comparing the power costs of two independent plants, the " Average Daily Wages per Man " " Figure of Merit of Coal " and " Load Factor of Load " must always be taken into consideration, and the plant having the lowest cost per kilowatt-hour

net output should be the proper standard for comparison. If it is desired to compare plants " A " and " B " when the former has the lower power cost, the corrected cost of plant " B " can be computed from the following formula:

$$Y = \frac{x\, y_i}{X} + \left[y_p - L\left(1 - F_L^{\pm 1}\right) - C\left(1 - F_C^{\pm 1}\right)\right] \frac{\sqrt[4]{x}}{\sqrt[4]{X}} \quad . . (3)$$

Y represents the corrected cost in mills per kilowatt-hour net output of investment plus production plus production repairs of plant " B."

y_i and y_p represent the original cost in mills per kilowatt-hour net output of investment and production plus production repairs respectively of plant " B."

X and x are the " Load Factors of Load " of plants " A " and " B " respectively.

L is the cost in mills per kilowatt-hour net output of all labor in all production and production repair groups with the exception of Group " P. A."

F_L is the " Reduction Factor " for labor as explained under item 9 of " Discussion of Analysis of Production and Production Repairs Cost and Data."

C represents the cost in mills per kilowatt-hour net output of coal (material only) in Group " P. E.," items 1 and 2.

F_C is the " Reduction Factor " for coal, as explained under item 29 of " Discussion of Analysis of Production and Production Repairs Cost and Data."

Use the reciprocals of F_L and F_C if the " Average Daily Wages per Man " is lower and the " Figure of Merit " is higher in plant " B " than in " A ".

For illustration we will assume the following approximate figures and compute the cost of plant " B " on the basis of " A:"

Plant	Load factor	Figure of Merit	Average daily wages per man	y_i	yp	$yi + yp$	L	C
A	50	14,000,000	$2.5	2.0	4.0	6.0	—	—
B	40	10,500,000	$2.0	2.5	4.5	7.0	0.13	3.0

$$F_L \text{ `` Reduction Factor '' for labor } = \frac{2.0}{2.5} = 0.80$$

$$F_C \text{ `` Reduction Factor '' for coal } = \frac{10{,}500{,}000}{14{,}000{,}000} = 0.75$$

$$Y = \frac{40 \times 2.5}{50} + \left[4.5 - 0.13\left(1 - \frac{1}{0.80}\right) - 3.0\,(1 - 0.75)\right]\frac{\sqrt[4]{40}}{\sqrt[4]{50}} = 5.57 \text{ mills}$$

That is, if plant " B " were operated on the same basis as plant " A " with regard to " Load Factor," " Figure of Merit " and " Average Daily Wages per Man," the cost of power per kilowatt-hour net output, including investment, production and production repairs, would be 5.57 mills, which is approximately 7.2 per cent lower than the cost for plant " A."

Summary

First. Standardization of method for determining the cost of all items that enter into the total cost of power, which is divided into three distinct sections.

Second. Method of analyzing the production and production costs and operating data for comparative purposes.

Third. Determining the relation between load factor and cost of power, so as to permit the comparison of costs per kilowatt-hour under varying conditions.

Fourth. Establishing an equitable basis for comparing the relative values of coals where the chemical analysis and price are different.

Fifth. Method of correcting for the cost of labor where the " Average Daily Wages per Man " is materially different.

In conclusion, the authors hope that this paper may be the means of arousing sufficient interest in this complex subject to insure a full and free discussion of the problems presented and that some standard method of determining power costs may result therefrom.

DISCUSSION ON "STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS". (STOTT AND GORSUCH), COOPERSTOWN, NEW YORK, JUNE 26, 1913.

Henry Floy: Turning to the last pages of the paper, it is a disappointment to find that the final formula, given on page 1650, in which one looks to find the solution of the problem discussed, omits a part of the "total cost" elements mentioned on page 1639. In fact the question may be fairly raised whether "General and Miscellaneous Administration Expenses" of one plant are capable of direct comparison with those of another plant upon the basis merely of output. These expenses really have little to do with the question of scientific perfection of design or efficiency of operation of a power plant. Proportioning such expenses to power costs in the relation of such costs to total costs, as mentioned on page 1636, may be unfair. This may be seen by considering the disproportionately large amount of the president's salary, for example, compared to his time or effort, that would be allotted to power cost, when based on the ratio of expense for fuel to the total expense. Perhaps a more equitable method of proportioning the general officers' salaries would be on the basis of letters found in office files relating to the different departments, or dividing auditing expenses in proportion to the vouchers passed for the various departments. Another omission from the formula presented is the failure to take into consideration for comparison, the substituted cost of water and its treatment for boiler and condensing purposes, which might be quite different, with appreciable effect on power costs, in the plants being compared.

Presumably the division of production and repair costs proposed, are along the lines of accounting established by the Public Service Commission of New York State, but pensions included in general expenses at foot of page 1622, are not in accordance with such classification. Neither is the item of interest included, as given among investments costs on page 1629. If variation from accepted rules of accounting is to be made, improvement in details should be expected. Why boiler insurance, for example, should be included as a part of repair costs and employees' insurance, with the attendant expenses, should be put in production costs, is not clear and is one of the apparent inconsistencies. It will be noted that in the substitution of one piece of apparatus for another, the authors make capacity alone the basis of capitalization charge, improved efficiency being entirely ignored. Depreciation is apparently taken to include only obsolescence and inadequacy, while extraordinary accident and "calamity", such as the floods which lately visited many plants in the central west, items which must be taken care of by reserves rather than insurance, are omitted.

The figures given in Table I, Life Expectancy, are stated to

be, what the authors believe, "fairly representative." It would be interesting to know upon what basis such statement is made, as the figures are not in accordance with those widely used and authoritative figures given, for example, in the speaker's paper on "Depreciation", presented before this Institute two years ago. It would seem only fair to criticize the use of figures which do not agree with those more or less well established and authoritative, unless the authors offer some explanation as to why their figures differ and reasons for their acceptance. The introduction of such random data, which is too common among writers of papers before this and other societies, results only in confusion and lack of uniformity, for which the profession is justly criticized. By way of further illustration, all buildings will not have the same life expectancy and the authors should differentiate between the character of buildings referred to; for example, wood, brick, steel or monolithic concrete, the lives of which will be quite different. The same with regard to scrap value. On what do the authors base their value of 5 per cent? Certainly it does not relate to wooden buildings, nor to concrete buildings, unless in exceptional cases, and the speaker has found 8 per cent is about the correct figure for the scrap value of brick and steel structures.

A similar line of criticism might be made of many of the other items mentioned in the table, the lives of which are unduly short, or of which the parts may be renewed almost indefinitely. The publication of such figures by men of such standing as the authors, leads to their use in misleading and unfair ways, by inexperienced and prejudiced engineers.

It is a mooted question whether depreciation should be considered as one account, of which wear and tear, obsolescence, accident and inadequacy are all separate classes, or whether maintenance and repairs should be considered separately and depreciation used merely in reference to other class of deterioration. The objection to dividing the item is that it is difficult to say when repairs and renewals are maintenance or depreciation. As a matter of fact, all wear and tear requires renewals, the distinction usually being, that when the renewals are small as to parts or in cost, they are charged to maintenance, and when relatively large or expensive, they are charged to depreciation. Such classification is purely arbitrary and in any system consisting of a large number of parts and the investment of many millions of dollars, all renewals can properly be treated as wear and tear. The cost of such replacements do not affect the income any more than does the wear and tear account affect the income of a company having fewer parts and smaller investment. Many companies are following the procedure (which is simpler and ordered by some Public Service Commissions, and therefore, in the opinion of the speaker, preferable) of establishing in advance, an annual amount, which is set aside for depreciation of all classes, usually appropriating

this out of revenue month by month. This depreciation a
is then charged month by month with the actual expen
made for maintenance, repairs and renewals, the balance
carried forward as a depreciation fund. This method of ac
ing avoids the constantly occurring and irritating quest
to which account, maintenance or renewals, the par
item being renewed, is properly chargeable. The impc
of having a definite and uniform rule for charging maint
and depreciation is at once apparent to anyone who is at
ing to compare classes of expenses in two or more plant
any case the proposal to periodically check and adjust the
amount set aside to cover depreciation is to be commend
is being done by some corporations.

It appears to be unjustifiable on the part of the autl
this paper, to use 5 per cent as the basis of return on
invested, even by way of illustration. The curve, Fig. 1,
ing the cost of power, based on a 5 per cent return, is misle
as no utility company can secure funds on any bas
the authors' own company very properly insisted upo
recently obtained a return of practically $8\frac{3}{4}$ per cent (inc
about one per cent for amortization) on its investment
New York subway, and the State of Tennessee this we
had to pay 6 per cent to refund its public debt. Why
should such an erroneous figure as 5 per cent be used?

In fact, any return on the investment in mere physical
erty, as apparently proposed by the authors, is entire
sufficient and unfair, if "total production costs" are being s
the proper intangibles or overhead capital expenditures
be included in order to obtain total production costs.

Item No. 28 defines load factor in relation to the ma
one-hour load; this is a longer period than would be ac
by many operators, as fifteen minutes, five minutes, o
less is frequently the basis on which load factor is esti
The statement that the cost of labor varies with the load
reaching a minimum at about 25 per cent, would undou
depend to some extent upon the size of the plant and n
of units. It would seem that the statement that the
per kw-hr. output varies approximately as the inverse
root of the load factor, should be amplified so as to show ac
the conditions under which this rule has been found to
size of units, capacity of station, fuel and labor costs, etc
what variations from these conditions are known it is p
to make without appreciably affecting the rule.

With reference to the paper as a whole, the question n
raised by some as to whether the subject discussed is a
one for consideration by a scientific engineering organi
The speaker desires to go on record as endorsing the pre
tion of such an eminently practical engineering paper
the Institute, and further to acknowledge an obligation
authors for the enunciation of their inverse fourth roo

which it is hoped will be found to apply, at least approximately, for all stations.

Carl Schwartz: Messrs. Stott and Gorsuch begin their paper by saying, "the need of some uniform method of accounting for the determination of the cost of power in steam plants has been long felt."

There is no doubt that this need exists because it is not alone difficult to draw a direct comparison between the cost of power from stations operating under different conditions, but in some cases even between two stations in the same locality, using practically the same kind of coal and operating under similar load characteristics.

The speaker is connected with a company which has for several years exchanged power station operating costs with other companies and knows that this exchange has been of benefit. In one case the cost of current for operation and maintenance of a modern power generating station containing four 5000-kw. units has been reduced from 0.67 cent in 1908 to about 0.45 cent per kw-hr. in 1912. It is true that the output of this station has increased from about 40,000,000 kw-hr. to about 76,000,000 kw-hr. per annum in the same period, and the average cost of coal has been reduced by about 11 per cent, still an appreciable amount of the reduction in cost of current can be attributed to the knowledge of other station performances. The cost of current at the present time is not as low as in some other stations of larger capacity; still, considering the price of coal, and the fact that the turbo-generators have a steam economy of about 18 lbs. per kw-hr., it is believed to be nearly as low as it can consistently be expected. If the steam economy of the turbo generators were 13 lb. per kw-hr. the cost of current would be about 0.37 cent.

The paper covers the elements entering into the cost of power in a comprehensive manner and gives a complete analysis of the conditions to be considered. The following comments are believed to be applicable.

A comparison of the cost of power should be made as simple and short as can consistently be done in order to relieve the operating companies of unnecessary accounting and computations, as otherwise some companies may decide that the expense of keeping their accounts in the manner prescribed and making the computations to bring their operating and maintenance costs on a comparable basis, exceeds the expense they feel justified in incurring. The more companies can be found to contribute to the statistics, the greater will be their value, and it would be unfortunate if all contributions to the cost statistics that are possible to secure could not be obtained.

A high degree of accuracy in making comparisons of station performances is desirable, still, some expenses cannot readily be compared, and for this reason it may be permissible to sacrifice a certain degree of accuracy for simplicity.

On pages 1620 to 1622 the items of production costs and production repairs costs are covered in full detail. To make a comparison between two or more stations it would seem that many of the items enumerated could be consolidated. If differences occur an investigation would readily reveal the reason and thus burdening the regular reports with a relatively large number of detail items of minor importance would be avoided.

Item PA, Management and Care, appears as an operating charge only. Some of the items thereunder, however, are chargeable likewise to maintenance and while the proportion chargeable to maintenance is small, still room should be provided for management and care under production repair costs.

The costs of the various items of production and production repairs are shown in cents per kw-hr. output. Some of these figures may not exceed a few hundred dollars per year and expressing them in cents per kw-hr. would take considerable time to compute and require many decimals.

I would ask Mr. Stott whether he sees any objection to the use of the total costs in dollars and cents for the detail items, making the distribution in cents per kw-hr. in the summary only, as given at the top of page 1623. An additional comparison would be afforded by expressing each of the items in percentage of the total.

Injuries to employees and other personal injuries and property damage is covered by group PJ-General, c and d. In investment costs, group IC, insurance covers the settlement of claims for personal injuries and property damage. Thus, accidents are charged against the operating account or to capital account, depending on whether the company carries insurance or not.

Fire or accidents will influence the cost of power from a station carrying insurance to the extent of the cost of insurance and from a station not protected by insurance will be correspondingly less, except in case of fire or accident, when the cost will be suddenly increased.

The accounts of a company carrying insurance and another not carrying insurance would, therefore, not be strictly comparable unless the condition for each station is made clear.

Mr. Stott covers very fully the matter of amortization and divides these charges into; first, physical depreciation, and second, functional depreciation. Physical depreciation is disposed of by charges against maintenance under the assumption that the plant will be maintained at 100 per cent efficiency.

For functional depreciation a comprehensive method is outlined which permits a readjustment from time to time to either make allowance for changes and additions or to correct certain assumptions as to the life of apparatus and machinery, should there be reason for doing so. While the flexibility of the method may be attractive, still it involves considerable labor and as an estimate of the life and the scrap value of the apparatus largely depends on the judgment of the person making the estimate, discrepancies are apt to occur which tend to offset the

advantages the method otherwise offers. Furthermore, the total life of 75 years for buildings may be impaired by radical changes after the shorter life of the machinery expires.

For comparing functional depreciation in place of this method, and for the sake of simplicity it is suggested to consider an average life of 30 years for the entire station and after making a deduction of 5 per cent for scrap value, charging a sufficient amount annually to equal, with interest compounded annually at 4 per cent, the prevailing investment.

By prevailing investment is meant the original cost of the plant complete excluding land but including all expenses chargeable to capital cost, like discount on the sales of securities, interest during construction, tests, preliminary operation engineering and contingencies. To this to be added annually the cost of additions and betterments less the original cost of any apparatus removed.

While it is realized that almost any form of depreciation offers room for objections, still it is believed that if some definite method like the above could be agreed upon and used as a basis for all comparisons of power station costs it would greatly simplify the work.

Referring to the Analysis of Production and Production Repair Costs, item 9, "average daily wages per man"—to compare the costs per kw-hr. net output of two independent plants on the same basis, a reduction factor is to be applied to labor only, the difference to be added to or subtracted from the total cost of production plus production repairs per kw-hr. net output.

This method would adjust differences in the cost of labor of different localities. It seems, however, that it would not allow adjustment in case the average daily wages per man are higher or lower by a different class of labor employed. For instance, one station may burn hard coal and be equipped with hand-fired grates requiring a certain number of men. Another station may be equipped with automatic stokers reducing the number of men in the boiler-room to a minimum though the average wages per stoker operator are higher than per ordinary fireman, thus raising the average cost per man for the entire station.

As to the reduction factor for labor, I have in mind the conditions of two stations, one burning soft coal with automatic stokers and the other hard coal screenings on hand-fired grates. The cost of labor and coal at these stations for the year 1912 compares as follows:

	Stokers.	Hand-fired-grates.
Net output, kw-hrs.	83,000,000	47,000,000
Boiler room labor, per kw-hr.	0.042 cts.	0.0984 cts.
Coal, per kw-hr.	0.314 cts.	0.3127 cts.
Cost of coal per 2000 lb.	2.37	1.63
Coal per kw-hr.	2.66 lb.	3.8 lb.
Total operation and maintenance	0.492 cts.	0.593 cts.

The cost of labor per kw-hr. in the station equipped with hand-fired grates is over twice as high as in the station equipped with automatic stokers due to the greater number of men necessary for hand-firing.

The average cost per fireman is less than per stoker operator and this condition, if Mr. Stott's method was followed, would lower the average for the entire station force.

I am not sure whether a method can readily be found to make an adjustment in satisfactory form and the reason for calling attention to these possible inaccuracies is not to suggest further refinement but rather to suggest simplification in the method of comparing the cost of power, even if some accuracy has to be sacrificed.

The curves in Fig. 1 of the paper clearly show the influence of the load factor upon the cost of power and those referring to the cost of production and production repairs appear to be sufficiently close to be used for bringing these costs on a comparable basis. While I believe that in this case, as in others, simplicity should be the keynote, still it will be difficult to find a simpler method that will give satisfactory results. After sufficient data have been collected it should readily be possible to adjust the curves and equations if necessary and, therefore, the method given by Messrs. Stott and Gorsuch should form a good basis for making adjustments for load factor.

Daily factor of load is expressed as:

$$\frac{\text{Actual net output for day of 24 hours}}{\text{Net maximum hour's load} \times 24} \times 100$$

and it is stated that load factor based upon the rated capacity shows a wide amount of variation, and for this reason it is proposed to base the load factor upon the actual maximum one hour load.

To deliver the maximum load a certain number of machines is required and their capacity may or may not agree closely with the load to be carried.

The load factor could readily be expressed by:

$$\frac{\text{Net output in kw-hr.} \times 100}{\text{Generator capacity running} \times \text{machine hours.}}$$

It is believed that this method will give more comparable results because the investment and the costs of operation and maintenance have less relation to the maximum hours load than to the capacity of the machines and their time of operation.

To adjust for the relative value of coal a method is proposed which corrects for the difference in B.t.u. the cost of coal and the percentage of ash.

There are other factors entering into the value of coal, namely, volatile matter, which may curtail the capacity of the furnaces by producing excessive smoke, sulphur, lime, iron and silica which may increase the operating labor and furnace maintenance, and the percentage of ash and amount of clinkers enter into the cost of ash removal.

Not all of the above items may be of sufficient moment to require adjustment, but some of them it would seem should be taken into consideration in comparing performances, because some plants may give better results than others though the figure of merit for coal, if computed on the basis suggested, is the same.

Section III covers General and Miscellaneous Administration expenses which is proposed to be charged to the cost of power in the proportion the total operating and maintenance cost of the power plant bears to the total running expense of the corporation.

With some companies a steam power plant is a relatively small item of its business and the distribution of the general and miscellaneous administration expenses as outlines will be difficult. It would be better to omit all of these items, because they do not affect the comparison of the cost of power sufficiently.

The scope of the program of comparing the costs of power could readily be extended to cover not alone the cost of power at the busbars of the power stations but up to the third rail shoes or overhead collectors of electric locomotives or the customer's meters of electric lighting companies.

The summary of a form for operating and maintenance costs from power stations to the third rail which has given satisfactory results is shown below:

Items.	Total cost	Cost per kw-hr.
Power Stations:		
Net a-c. output, —— kw-hr.	....	....
Operating labor,		
Operating material,		
Maintenance labor,		
Maintenance material,		
Total at power stations,		
(1) *Total at Train Shoes,*	....	
Substations:		
Net d-c. output, —— kw-hr.	....	....
Operating labor,		
Operating material,		
Maintenance labor,		
Maintenance material,		
Total at substations,		
(2) *Total at Train Shoes,*	....	
Cable Department:		
Alternating current:		
Total a-c. input to subs., etc., —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total a-c. cables,		
(3) *Total at Train Shoes,*	....	
Direct current:		
Total d-c. output at third rail, —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total at Train Shoes,		
Third Rail:		
Total d-c. output at third rail, —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total at Train Shoes,		
Grand Total at Train Shoes,		

(1) This figure to be obtained by multiplying the cost per kw-hr. at power station by 100, dividing by efficiency in per cent from power station busbars to train shoes.

(2) This figure to be obtained by multiplying the cost per kw-hr. at substation d-c. bus bars by 100, dividing by efficiency in per cent from d-c. substation bus to train shoes.

(3) This figure to be obtained by multiplying the cost per kw-hr. at substation a-c. bus bars by 100, dividing by efficiency in per cent from a-c. substation bus to train shoes.

The fixed charges for transmission lines, substations and third rail could be handled in a similar manner as for power plants.

The above can be briefly summarized as follows:

1. Condense the comparison and simplify the accounting and computations as far as possible.

2. Space should be allowed under the maintenance account for certain expenses under management and care chargeable thereto.

3. For all detail items total cost figures could be used instead of cents per kw-hr., to save labor and avoid small decimal fractions. The cost of items in the summary if expressed in per cent of total would permit additional comparison.

4. Simplify the method of calculating functional depreciation.

5. The average daily wages per man are not only determined by the cost of labor in different localities but also by the nature of the equipment and the class of labor employed.

6. To express load factor the following expression is proposed:

$$\frac{\text{Net output in kw-hr.} \times 100}{\text{Generator capacity running} \times \text{machine hours.}}$$

7. The figure of merit and reduction factor for determining the relative value of coal is believed to require additional adjustment. If a certain quality and cost of coal could be agreed upon as standard, comparison should be facilitated.

8. It is suggested to omit Section III, general and miscellaneous expenses.

9. The scope of the comparison of the cost of power could be extended to cover the cost of current up to the point of consumption.

In closing, the speaker wishes to express his belief that the authors' paper covers the subject so fully that with relatively minor revisions it should form an excellent basis for the Standards Committee as a standard method of comparing the cost of power.

William McClellan: It seems to me that this paper must be taken, as the authors have suggested, by a committee of the Institute and gone over line by line. More simplicity appeals to me; certain mechanical features about the report,

such as a better choice of letters, corresponding to classes, I think, can be somewhat improved.

Inasmuch as I have had some experience with public service commissions from the commission side, I must say in answer to the fear that the companies will object to doing the various things which are suggested in this paper, that there are two answers.

First, the companies themselves are finding out that there is nothing to object to. A number of companies in New York City are comparing costs with each other, and the result of this comparison is more or less public, but not entirely so. In the second place, companies will have to do it sooner or later.

The desirability of this sort of thing is, first, that we want it for ourselves—the companies themselves need it. A man who does not know just what he is doing in the way of costs in the production of power is not running his business properly. In the second place, the man who is not able to compare what he is doing with what the other man is doing, cannot make proper progress. First, it is necessary to know what we are doing for the sake of having the knowledge, and secondly, to compare our operations with those of others, which is important in all departments of life. Otherwise we cannot tell whether we are moving or not, and especially whether we are moving in the right direction.

I like the general plan of the paper very much. I think the Institute has had a tremendous lot of work done for it of the very highest quality. Just where certain items should be placed, I think there is a little doubt. When I first read the paper, I wished for educational purposes that depreciation could be put among production costs. Many men fail to realize that depreciation, or amortization, if you please, is an expense. There are many men who say: "Why should we take part of our profits and put them into depreciation?" The reply is that you are not earning profits until you have paid for every item you require in the operation of a plant. When the machine is operated, it is burning up just as surely and certainly as the coal under the boiler. You do not see it going on in just the same way, but it is as surely taking place.

One of the speakers spoke of calamities. If a building is destroyed by fire, I do not know how far you will be able to go into a depreciation fund for that. I think from the viewpoint of modern methods you would be unfortunate if you did not have insurance on the building.

Take the division of depreciation into large and small repairs. It is an operating expense. There is a question if you reduce these things into a formula, as to what effect it will have. You may pay for the repairs directly out of this year's operating expenses, or you may defer them and pay them five years from now in the form of larger repairs. That is a matter of bookkeeping, but when you introduce depreciation into a formula

and have the results comparable with the results of other companies, it does make a difference, and that would require a great deal of thought.

Companies must be put in different classes, or you will not be able to compare them justly. It would not do to compare a small station with a large one, or one station with another station of a totally different type. Therefore we must put the stations, or whatever we are comparing, into various classes, so that they can easily be taken care of.

Finally, I want to make a motion, Mr. Chairman, if I may. It has been suggested by the authors, and in following out their wishes I desire to move that it be the sense of this meeting that the suggestions made in this paper be referred to the Board of Directors of the Institute, that they may refer it to a proper committee for immediate action, the meeting believing that it is extremely important that the subject be brought as soon as possible to a practical basis for use by the Institute members.

C. O. Mailloux: I take pleasure in seconding the motion. I consider that the Institute is to be congratulated again in having a paper of this kind from Mr. Stott. It is especially to be congratulated upon the fact that all of Mr. Stott's papers on central station economies have been read before the Institute. You do not appreciate that now so much as you will a few years from now, when you look back and see the evolution of central station economics and come to realize that Mr. Stott is the man who really put the matter on a sound basis. Some of his papers will then be recognized as classics and we will appreciate their value. A few years hence engineers will look upon Mr. Stott's papers with the same high respect that is shown the classic writings of Rankine.

I think it is very important, as Dr. McClellan said, that this paper should be put in the hands of an intelligent committee especially fitted and qualified to deal with the many questions which the paper brings up, so that the valuable data and information contained in this paper may be put in such form that it will be made available to the Institute members and to the profession of engineering in general.

Peter Junkersfeld: I feel that too much has, perhaps, been attempted. However, as Mr. Stott has said, the matter is presented as a target, and with that explanation, it is very well put, indeed. If this paper is referred to a committee in accordance with the motion pending, I would suggest that such committee look over the field carefully and see what has already been done in this connection.

We must not assume that no standardization so far has taken place. I would call attention to the fact that both the National Electric Light Association and American Electric Railway Association have a standard classification of accounts, and as far as power house general classifications go they are practically the same. The National Electric Light Association has nine

general headings for the power house expense and the American Electric Railway Association eight. I have here a memorandum showing the number of subdivisions under the various headings of power plant expenses as divided by the Commonwealth Edison Company, which follow closely the National Electric Light Association; those proposed by Messrs. Stott and Gorsuch; and those proposed by the American Electric Railway Accountants Association. (See table on next page.)

The most important thing is to consider the general headings, say eight or nine, so that when we compare these in different plants we will know what we are talking about. If we find a discrepancy, then we can analyze and subdivide, but the subdivisions must, in many cases, be different, because there are many local conditions that will affect one place as compared with another, but the general headings ought to be alike.

There are many details which might be discussed. One very important point made was that the net output should always be considered and not the gross output. It is surprising how many people throughout the country make that error. It is obvious that it is not worth any further discussion. Net output, in my judgment, should always be used, and there is no excuse for using gross output.

So far, I am speaking entirely of operating cost. Now, on the investment side of the business, standardization is going to be more difficult, and, I would suggest, as a matter of practicability, and of making the most headway, that your committee concentrate its efforts, first, on comparison of operating costs.

I am afraid if they attempt to standardize the entire thing at one time, they will meet with opposition in different parts of the country. There are many conditions all over the country where, if a company should show all its investment costs, it might be subject to difficulties from people who, through ignorance, or through intent, might misuse this information.

It is possible, also, to segregate general expense a little too far in that connection. You cannot in any line of business, whether it is a central station lighting company or a traction company, assume that the power house is an absolutely independent business by itself. Therefore you must have some general expenses which cannot be apportioned correctly. You can approximate them, but to say as a matter of record, that month by month so much should go against that station, and so much against another, is not always getting at it in accordance with the actual condition. There may be some extraordinary work, or some contingency, that will involve one power house a certain length of time. During this time any general expense you ordinarily apportion to that power house would be far too low, and when that state of affairs occurs you are fooling yourself. General expenses do not have a constant ratio to each of different elements of the business.

Load factor is very important, and I am glad the authors

CLASSIFICATION OF POWER PLANT EXPEN

Commonwealth Edison Company	Proposed by Messrs. Stott and Gorsuch	American Accoun
(1) Labor for operation: 6 subdivisions.	Management and care: 10 Subdivisions. Boiler Room Labor: 12 subdivisions. Engine room labor: 7 subdivisions. Electrical labor: 9 subdivisions.	Powerhou No sub
(2) Fuel: 5 subdivisions.	Fuel: 7 subdivisions.	Fuel: No sub
(3) Water: No subdivision.	Water: 6 subdivisions.	Water: No sub
(4) Lubricants: No subdivision.	Lubricants: 2 subdivisions.	Lubricant No sub
(5) Station Supplies and expenses: 7 subdivisions.	Production supplies: 7 subdivisions. Station expenses: 4 subdivisions.	Power pla No sub
—	Operating general expense: 5 subdivisions.	
(6) Maintenance and repairs of station building and property outside of station building: 4 subdivisions:	Building repairs: 6 subdivisions.	Building r No subd
(7) Steam equipment repairs: 8 subdivisions.	Repairs to furnace and boilers: 10 subdivisions. Repairs to boiler accessories: 8 subdivisions. Engine repairs: 5 subdivisions. Repairs to engine accessories: 5 subdivisions. Repairs to piping: 10 subdivisions: Repairs to tools: 4 subdivisions.	Equipmen No subd
(8) Repairs to electrical: 4 subdivisions.	Repairs to electrical generators: 5 subdivisions. Repairs to electrical accessories: 8 subdivisions.	
—	Repairs general expense: 4 subdivisions.	
(9) Purchased power: No subdivision.		Purchased No subdi

SUMMARY.

	General Headings.	
Nine.	twenty.	E
	Subdivisions.	
Thirty-four	One hundred and thirty-four	N

brought it up. They have pointed out that there is a good deal of misunderstanding all over the country as to load factor. Every time load factor is used it should be stated whether it is daily, monthly or annual load factor, and what kind of peak it is based on. In dealing with load factors and maximum demand, we should be very definite and know just what we are using, know that it is not guess work, something really substantial, an actual observation of all the elements that make up load factor.

In figuring investment costs, spare capacity is a big item. You may be able to operate under certain conditions with 10 per cent spare capacity. Under other conditions, with a growing business, that may be much too close. I know of situations where 20 per cent is too close, because of the rapid growth of the business. That does not mean the company always carries 20 per cent, but that is the figure when everything goes well. If there are labor troubles or manufacturing difficulties, that 20 per cent in one year may go down to 5 per cent. Such possibilities must be provided for.

As to maintenance and depreciation, these items often do not tell the whole story. If a man has a very low maintenance account it is well to look back of that account and see what his machinery looks like. We must consider very definitely both maintenance and depreciation when we speak of these terms. When we look over the past, it is one matter to assign a certain amount for depreciation, but when we look ahead we do not know what it is going to be, and we must allow a reasonable amount to cover what it may be. Past and future depreciation are two separate things and should never be confused.

D. B. Rushmore: The cost of power is the basis of nearly all engineering work. Practically everyone is manufacturing something in which a cost comparison is the basis for decision between different paths of action.

The specific point under discussion this morning is one phase of a very general subject that includes the cost of articles manufactured in practically every walk of life. The farmer is manufacturing his products, the railroad man manufacturing transportation, the electrical engineer manufacturing electricity, or whatever else it may be, and the very fundamental part of this engineering work is the cost of the product. This cost is generally recognized as being divisible into a quantity which varies according to the output, and when the consideration of this specific case comes up during the coming year it will be of interest to those working on it to consider the broader underlying fields which are necessarily involved.

The usefulness of this paper at the present time is not only to operating men, but also to a field in which the speaker happens to be engaged, that of manufacturing companies. At the present time the difference between hoisting by compressed air or hoisting by electricity is very largely one of the cost of the output,

and the basis of comparison is not very easy. It is very difficult to get the advocates of different systems to agree regarding the items which should enter into the comparison, and until such a decision is reached it is very hard to play the game in a proper way.

In connection with the amortization, there is a different class of amortization in the general field involved in those pieces of machinery and in those products which have a natural life. An incandescent lamp has a limitation to its usefulness which is more or less fixed, a motor approaches the dividing line. We expect to wear it out and throw it away. Larger machinery does not wear out, but individual parts do, and a few parts can be replaced and the condition of the machine kept up to its original shape.

The fact that up to the present time it has been very difficult to determine the actual costs of power for different plants and operating conditions, represents a condition fully justified by the fact that for a concern, individual or company, to give out its manufacturing cost, it must be in a position where these cannot be used to affect its condition adversely, and the advent of the Public Service Commission, with the protection that it gives, along with its other features, is one of the reasons why it is now permissible to give more publicity to these figures. A suggestion is made for the coming year that in order to get the most benefit from the tree which is going to grow from this seed planted by Mr. Stott and his associate, that an effort be made to bring the engineers of the Public Service Commission into the Institute and to have them in some way affiliated with that part of the organization which will be active in formulating these principles.

L. P. Crecelius: The abstract of this paper begins with a statement that power cost should be upon a basis of per kilowatt-hour net output. This looks like a good beginning, and the same principle as laid down here should be applied to every one of the various groups which follow.

In the case of I, Production and Production Repairs Costs: The proposed method seems proper, but care should be excercised before adopting it as standard in its present form to avoid upsetting such existing classifications of accounts as are now standard, in extensive use and under which a multitude of reports are made to various local, state and national utilities commissions. Such little differences as appear in the treatment of the various accounts under this heading as presented in the paper are relatively unimportant and no great difficulty should be experienced in getting them in a proper shape.

In the case of II, Investment Costs: Exception is taken to the proposal of apportioning franchise and revenue tax and charging some of this expense out as cost of power. The reason for this will be given later. The miscellaneous item of this group is open to the same criticism, as will be pointed out later.

In the case of III, General and Miscellaneous Administration Expenses:

Under this group are a few items which may properly be charged out as cost of power, in the case of certain corporations, but on the other hand, it is proposed in this paper to charge as cost of power, a great many other items which in my belief cannot and should not be included.

The time is indeed opportune for the presentation of this committee report to the American Institute of Electrical Engineers with the request that it go before the Standards Committee, in fact it is past opportune, and I welcome the opportunity thus afforded to present my views on this important matter. There is no question before the power engineer which approximates in importance the question, "what is the *true* cost of power"? He finds himself continually confronted with this question, especially, when the proposition comes before him to decide whether it is wise to continue to manufacture power or whether it would not be better to purchase power from someone who has the peculiar gift of making it cheaper. Again and again, in working up this case little or no information is at hand and rarely can anything better be found to substitute imaginary estimates in order to secure the significance of the value of a great many obvious but ordinarily obscure items such as, for instance, administration expense, casualties, extraordinary maintenance, etc. The greatest use to which this method of determining and comparing costs in steam plants will be applied is in connection with extensions and betterments to existing power plants, and in the matter of determining a proper basis for the purchase of power. Therefore, let the method and its arrangements be such that the true cost of power will result.

My objection to the proposal of permitting much of the general and miscellaneous administration expense of a corporation other than a purely power producing concern to be charged out as power cost is based simply upon this illustration; a railway company operating power plants, is in need of betterments for extensions or otherwise, and is at once approached with the subject of purchasing power. An analysis of its present cost is made and compared with other plants for such information as is available and the possibilities of the betterments as reflected upon the future power cost are brought out. Now, however, if the cost of power is found upon the basis proposed in this paper, it is burdened with a great many foreign miscellaneous expenses such as the salaries of executive officers and the presidents' or directors' travelling expenses to a convention, a portion of which is here proposed to be called power cost; the chief counsel's expenses in connection with appearing before a utilities commission on some question other than power, is also called power cost, and so on. When all these items are added to the cost of power under this plan, it is decided to purchase power rather than to make additional

investments, and the old equipment is scrapped and written off the books. The result: it is soon discovered that the administration, general and miscellaneous expenses still continue with the corporation which now purchases its power; no reduction in these items is noticed; an allowance for this expense has been made in the cost of the purchased power and we now find the situation where for a great many years the railway is obliged to pay this expense doubled.

The ready means which were at first available to relieve itself of a portion of the expense of these items on the score of power cost as had been practised before shutting down its power power plants, are now gone; secondly, the railway has permitted this previous expense which was called power cost, to be added to all the power which it now purchases. In the face of this situation, my suggestion is, first, that a good rule to follow with reference to these miscellaneous revenue and income tax expenses, administrative office and miscellaneous expenses, is to charge only that portion which would disappear in the event that power was purchased, and secondly, that the report as presented by this committee should receive more consideration in this respect, again going before a committee and every angle of this complex subject being carefully analysed.

W. G. Carlton: The summary of operation and maintenance costs or as called by the authors, the "Production and Production Repair Costs", is sufficient for moderate size power stations without going into all of the detail given on pages 1620 *et seq.* A monthly comparison on substantially the same basis as this summary has been made for several years by six electric power stations in and near New York City; these power stations having monthly outputs ranging from 2,000,000 to 18,000,000 kw-hr. This method was shown by Mr. B. F. Wood in a paper on *Electrical Operation of the West Jersey and Seashore Railroad,* presented at the annual convention of the Institute at Chicago in 1911.

In addition to giving the unit costs per kw-hr., it is frequently convenient to have the total cost stated, especially in the smaller items, since a better idea of their importance can be grasped from the total money involved than from the unit costs.

August H. Kruesi: This paper will be the more rapidly adopted and be more valuable the more general it is made. I recommend that its scope be extended to include those electric light and railway companies which also produce steam for heating, of which there are a large number in this country. The method would then be applicable to a very large number of industrial power plants which not only produce electrical power, but exhaust steam for heating, and live steam for manufacturing.

I believe in connection with the comparison of costs that the load factor is not sufficient; that we ought to take into consideration not only the machine load factor, but what we may call the station capacity factor. We might divide both the max-

imum load and the monthly output by two and still get the same load factor, but a large part of the operating cost per unit of output would be twice as great, the fixed charges per unit of output twice as great, and the costs tremendously affected.

The proposed inverse fourth root relationship is represented by curves as shown in the paper, or as in Fig. 2 herewith. I suggest that instead of dealing with the costs per unit of output we should deal with the total output and the total cost. The relationship is then represented by an approximately straight line as in Fig. 1 herewith. This I think will facilitate comparison

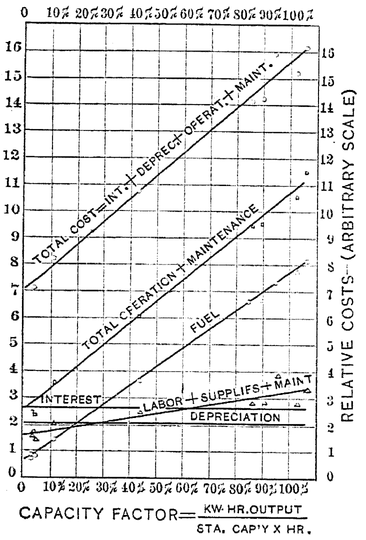


FIG. 1—RELATIVE COSTS FOR 4000-KW. POWER STATION

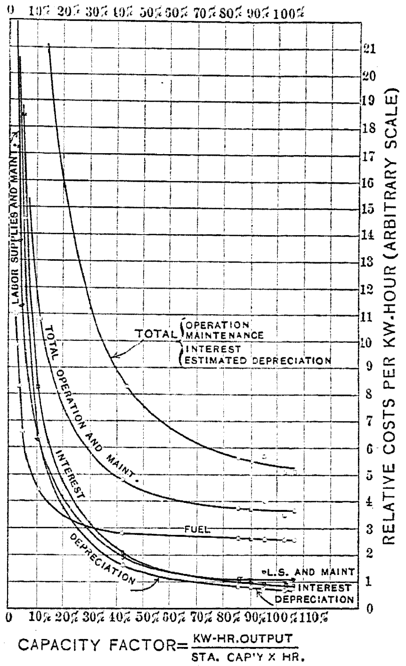


FIG. 2—RELATIVE COSTS FOR 4000-KW. POWER STATION

and will be more readily understood by the accountants and the executives who have to deal with such questions, as well as by the engineers. If it is desired to deal with an equation rather than by plotting, Fig. 1 permits an equation which is much easier to use. The actual performance of a certain steam turbine station is represented by Figs. 1 and 2. Whether the plotted results will always lie on a perfectly straight line or not does not matter and does not make the method suggested any less accurate than the proposed inverse fourth root method.

D. C. Jackson: This communication of Messrs. Stott and Gorsuch is an important addition to the extended series of

truly classical papers which have been produced by Mr. Stott and his assistants. There are two quite distinct and yet closely related features in this paper. One is the proposal that suitable records shall be kept by power companies, and the presentation of a method of keeping them. The other is the statement of Mr. Stott's new inverse fourth root rule of the cost of power as it is affected by load factor. In respect to the latter, I have made some tests of the application of the rule to certain relatively small generating stations which have enjoyed a steadily improving load factor for a number of years and in which the supervision has been good. Comparing the cost of power production plus repairs in the different years, the results come out in satisfactory accord with the inverse fourth root rule, which indicates that we here have a rule which is not only applicable to enormous plants but that it is of general applicability. The rule may therefore be made of much value in studying the advantage to an electric power enterprise which may arise from obtaining a load of improved load factor. It cannot be applied, however, as between two different plants unless they are alike in character and organization. Take one plant with 30 per cent load factor annually, and another plant with 45 per cent load factor annually, and if they are quite different plants, you cannot compare them by this rule without making a prorate with respect to the cost of labor and the cost of coal. Even then one can scarcely expect to get an important comparison between two such plants through the inverse fourth root method. Some other curves will apparently have to be made besides those which Mr. Stott has suggested in the paper, to obtain value from such a comparison, yet it is worth trying to extend the method so that it may be used to find a relative figure of merit for plants under diverse conditions.

I want to speak of the need of extending this study of cost of power beyond the power house. The power house cost is not the whole cost of power to the average company. The average company is not only a manufacturer, but a distributor, and the delivery cost is really one of the most important items in a large number of cases. In fact the delivery costs may be greater than the production costs, and under these circumstances we should not be satisfied to stop at a study of power house costs. This is a problem that needs the joint consideration of the engineers and the auditors, and until such coöperation is brought about in our electric companies, power costs will not be fully figured and known and the lowest profitable prices which can be made for classes of customers will not be determined.

I will not attempt here to go into the details of this paper. A classical paper does not ordinarily lend itself to discussion in detail; and this paper like its type is a stimulus to study rather than discussion.

Ralph D. Mershon: Professor Jackson is in favor of extending the study of power costs to the distribution system. Before doing so it would be well to agree as to the meaning of some

of the terms usually employed in such a discussion. For instance, we should have an authoritative and acceptable definition of "load factor." As it is now, when a man talks about load factor one cannot be sure just what he means. Some persons associate the load factor with the station, making it depend upon the load in relation to the rated capacity of the station. To my mind the load factor is a characteristic of the load and has nothing to do with the station. The Institute has a definition of load factor, but this definition is far from being definite, and does not appear to be acceptable to other electrical organizations. The endeavor should be made to give the terms we employ such definitions as will be acceptable generally, and so explicit that when a term is used there will be no uncertainty as to the meaning it is intended to convey.

P. W. Sothman: I agree thoroughly with Mr. McClellan that we should publish statistics freely. The advantage gained from statistics is very obvious, in that they will help us to make comparisons and stimulate us in our endeavors to obtain the highest efficiency.

I think Messrs. Junkersfeld and Mershon are right with regard to the load factor. The more I think of it, the less I find I know about it. The matter should be referred to the Committee on Standards of the Institute for elucidation.

H. M. Hobart: I think a brief allusion should be made to the influence of power factor on the cost of manufacturing electricity. It is apt not to be recognized how greatly the power factor affects the cost. It is generally thought that it affects exclusively the cost of the transmission line, the substations and the distribution system. But when you go into the matter seriously you will find it makes a decided difference in the cost of the electricity as delivered at the outgoing cables of the central station. I am of opinion that in these schedules some account should be taken of the power factor. Of course, also, the *kind* of electricity, the *form* in which it is delivered to the outgoing cables, makes a large difference. When it is delivered in the single-phase form it costs more than when it is delivered in the three-phase form. The turbines may be of the same size, but when you take into account the increased size of the generators and their lower efficiency when designed for single-phase, it is found to make a very decided difference. The difference is apt to be confused with the circumstance that this single-phase electricity for the purpose for which it is now required on a large scale is always associated with a low power factor. The aggregate result of being required to deliver the electricity at a low power factor, and at the same time in the single-phase form, is to occasion a very serious difference in the cost of electricity, which certainly must be taken into account. It is utterly erroneous to consider that the two kinds of electricity can be produced at substantially the same cost.

I was glad to notice in the paper and also in the discussion the increased tendency to express the capacity of the station

in terms of the millions of kilowatt-hours per annum to be delivered, rather than in terms of the rated capacity in kilowatts, because when you come to the rated capacity in kilowatts it is difficult to apply a definite rating to a station. In looking into the matter of the thermal regulation of turbo-generators, one finds that a large generator which will deliver an output of unity for a given ultimate temperature of its windings on the coldest day of winter, will have its capacity brought down to something like five-tenths on the hottest summer day, so that you can hardly put on the nameplate of the generator a rating in kilowatts, when it varies from two to one from the coldest day in winter to the hottest day in summer, provided you want to consider that the limitation to the output of the generator is the temperature of the hottest part of its windings.

Paul M. Lincoln: I want to make a few remarks on the matter of load factor. We have been told that when we talk about load factor we do not convey any idea of what we are talking about. I do not think that is exactly true. I might use, as an illustration, that if I should say I saw a dog on the lawn, you would know in general what I was talking about, but you would not know whether I was talking of a dachshund or cocker spaniel, or some other kind of dog. If I wanted to convey the idea of what particular kind of dog I was speaking about, I should have to say I saw a male cocker spaniel pup a few weeks old, having such and such characteristics. We are doing exactly the same thing, when we speak about load factor. When I say load factor, you know in a general way what I am talking about. It is a generic term, not specific; it is the difficulty with the speaker, as a rule, that he does not define exactly what he means. But if I should speak of the daily load factor, based on a fifteen-minute maximum, you would know what I meant, and if I should speak of a yearly load factor, based on a one hour maximum, you would know what I was talking about. The term "load factor" is perfectly defined in its generic sense, and if the speaker wishes to be more definite, it is up to him to put in the proper qualifications.

Ralph D. Mershon: Will your remarks apply to the case where the load factor is the ratio between the average load on the station and the generating capacity you have in it?

Paul M. Lincoln: That is not load factor, that is something else.

Ralph D. Mershon: Most people call it load factor.

Paul M. Lincoln: Load factor is something that applies to the load and not to the station that carries the load.

W. S. Gorsuch: The formula on page 1650 has been criticised by Mr. Floy, because "general and miscellaneous administration expenses" are not included. These items can be added in the same way as "Investment Costs," making correction for load factor only, as explained on page 1648. However, it is not the purpose of the formula to express the total cost of power but to show after applying correction factors the

relation of those costs which depend upon the station design, efficiency and management, as illustrated and explained on pages 1646 and 1647.

To compare two plants from a purely operating point of view, it is proposed to correct for the "Average Daily Wages per Man" and the cost and quality of coal or "Figure of Merit", as these two items are materially affected by local conditions over which the station manager may have little or no control. The other items of production and production repairs are practically factors of station condition, design and management and can be directly compared without making any corrections. The Investment and Administration Costs are independent of how a station is operated or managed, and these items can be compared directly on kw-hr. net-output basis without any corrections, to see whether or not either station is unduly burdened with such charges. One plant may be carrying more surplus capacity than is necessary and for which there may not be any demand in the immediate future. If a correction factor were applied to every item of cost, a hypothetical station would be set up equivalent to the plant taken as standard of comparison, with the natural result that the power costs for both plants would be practically the same.

I do not know of any life expectancy table that is generally accepted by engineers, as has been stated. Further, the life expectancy table used in the illustration is not given for the purpose of setting up a standard, for there cannot be any standard in the sense that the table is used in the paper. An independent life expectancy table should be established at the beginning for each plant and readjusted at certain periods. If two plants are equipped with similar apparatus and installed about the same time, the life expectancy tables at the start would naturally be the same. If, on the other hand two plants should be installed a period of years apart with similar equipment the life expectancy tables may be correspondingly different for certain apparatus. One company may purchase and install apparatus that will soon become obsolete while another company may have had similar apparatus in service for several years, in which case it would not be consistent to apply the same life expectancy table when each plant was put in operation.

In comparing the power costs of any two stations with a view to purchasing and interchanging power or combining plants, it is essential to see that the life expectancy tables are not relatively too low or too high. What the whole scheme really amounts to is to establish a reasonable independent life expectancy table at the beginning for each plant, so that the percentage estimated to be set aside will be sufficient to replace the apparatus when it becomes obsolete or inefficient.

The expenses of personal injuries, other property damages and pensions, chargeable to the power plant should be determined independently, as they are relatively small in comparison with those of other departments of a railway or lighting company.

These expenses may be incurred by straight operation or during repairs and it is proposed to charge them to production or production repairs as the case may be.

Mr. Schwartz seems somewhat apprehensive regarding the application of the "Reduction Factor" for labor when comparing a hand-fired with a stoker-operated plant. While it is true that there will be more men, and that the "Average Daily Wages per Man" may be lower in a boiler room that is hand fired than in one using mechanical stokers, yet it is equally true that one plant may have too many other classes of men in the station due to bad management, poor arrangement and kind of equipment etc. If it is desired to know what the stoker operated plant with its entire equipment can do, provided the lower price of coal and lower (possibly) "Average Daily Wages per Man" of the hand fired plant can be obtained, it will be perfectly fair to apply the "Reduction Factors" for coal and labor as outlined in the paper. It may be that a hand-fired plant has a lower "Average Daily Wages per Man" with practically the same "Figure of Merit" of coal as the stoker-operated plant with which it is being compared, in which case it will be necessary to increase the cost of labor of the hand operated plant for comparative purposes.

In reply to Mr. Schwartz's suggestion that in determining the "Figure of Merit" of coal, volatile matter, sulphur and other ingredients than that of ash should be considered. I wish to say that it would be very difficult to correct for many of the factors, and further, the variation of some is so small as not to materially affect the "Figure of Merit". For illustration, in comparing two coals it will require a difference of 30 per cent in hydrogen to make a difference of about 1 per cent in the "Figure of Merit".

Regarding the question whether it would not be better to give the total cost of each item under the various groups instead of the cost in cents per kw-hr. net output which in some cases will be a decimal of several ciphers, it will not be possible to compare corresponding items of two stations on the same basis unless reference is made to the kw-hr. net output.

The charges covered by Group P.A. "Management and Care" would naturally be distributed among all the other groups, but this would be very difficult to do, as some rule or assumption of distribution would have to be made which would vary for different stations. For comparative purposes it seems to be advisable to group these costs as outlined.

If the percentage to be annually charged to the "Amortization Fund" is determined by using the average weighted life and the total cost of the plant, it will be found after a period of years that there will not be sufficient funds to cover the required replacements. The proper way to arrive at this percentage is to determine the amount to be set aside annually for each main item as outlined in Table I and then determine the rate by taking the total annual charge and the total amount to be amortized.

Regarding the question as to whether the relationship between load factor and cost of production plus production repairs as expressed by the inverse fourth root law is applicable to small plants, this law will hold for plants of 5000 kw. capacity and probably smaller.

There seems to be a difference of opinion as to whether the "General and Miscellaneous Administration Expenses" should be included in the cost of power. For the purpose of comparing the cost of power from an operating point of view, it is not necessary. However, for the purpose of exchanging or selling power a portion of these expenses should be included in order to obtain the true cost of power to the company. A portion of the administration expenses is required to make and keep the plant a going concern, such as the purchase and distribution of fuel and material, drawing up contracts for materials and apparatus used in repairs, adjusting claims, relief, handling pay rolls, etc. Taxes are also imposed on the company for the privilege of operating.

Aside from the above, if a company desires to determine whether it will be cheaper to purchase power, it will be necessary to exclude such items that will not disappear and include those that will disappear in the event of power being purchased. This not only applies to "General and Miscellaneous Administration Expenses" but also to "Investment Costs". For instance, the bondholders may require that the plant be kept intact and not dismantled and scrapped. In contemplating the purchase of power, the conditions should be considered under which the proposition is made before comparing power costs, as items that will disappear in one case may not disappear in another.

I do not see that it is necessary for any classification of accounts that may be decided upon for determining and comparing power costs, to conform strictly to any Public Service Commission Classification. However, the grouping should be arranged so that any Public Service Report can be compiled from it.

The amount of the miscellaneous items in each group will be relatively small as any appreciable expenditure can be charged to a definite item.

E. D. Dreyfus (by letter): We have long felt the need of establishing criteria for measuring the performance of our power plants. If the movement Mr. Stott and his associate have inaugurated will be conducted in the manner it deserves, benefits to industries are bound to result. Some stations under efficient and progressive management have established results which should be fairly taken as bench marks from which other stations should measure their performance.

Conditions, of course, vary widely and the authors have focused attention upon those which were of the most serious nature and have proposed formulas to reduce the operating conditions of different plants to a more or less common basis.

In connection with the formula at the bottom of page 1648, it is the writer's opinion that in a great many plants there would be either difficulty or a great deal of additional work to adequately and satisfactorily determine the percentage of combustible in the ash. For simplification I would propose that this formula be modified so that the "figure of merit" could be ascertained directly from the coal analysis and the total effect of the percentage of the ash taken care of somewhat in accordance with the results obtained by Mr. W. L. Abbott in a long series of tests conducted in Chicago upon the effect of variation of percentage of ash in the fuel and which was published in the proceedings of the Western Society of Engineers, 1906. Also, I wish to call attention to the fact that the use of the long ton confines this formula, more or less, to sections in and around New York. I believe according to government reports that over ninety per cent of the coal mined is sold on the short ton basis.

The authors have adopted a factor termed, "The Average Daily Wages per Man". In this connection I might mention another point which might have some bearing, and that is that some operating companies work on a very much closer margin as regards the number of men engaged in running the power house than others. Some companies hold more men in reserve for emergency and figure that the cost of this insurance is worth while; while, on the other hand, other companies view the matter from the standpoint that it is best to keep the labor cost down to the minimum and economy thus effected will more than offset any probable loss due to emergency which might have been largely offset by having extra men working around the power house and in readiness to do emergency duty.

As the writer understands it, as far as the present analysis goes, it is probably the intention to compare stations of practically the same size. Although it might seem a difficult matter to establish a relative scale for plants of different capacity. I believe this phase could be worked out in a satisfactory and dependable way through a synthetical study. There will probably be times when it will be desirable to compare stations of different capacities regarding which the other operating conditions are very similar.

As is obvious, the question of power plant comparisons is, to a large extent, involved, and the authors are to be highly commended for the steps they have taken to overcome the apparent obstacles and make comparisons of practical and definite value.

Charles S. Ruffner (by letter): The power costs of two given plants will differ because of size, cost of labor, fuel and other supplies, the average use of maximum load or load factor, the relation of maximum demand to total capacity, investment, efficiency of management, and the degree of proper coördination of each unit of equipment as regards relative capacity and location. The paper of Messrs. Stott and Gorsuch attempts to

compare power costs by eliminating or equating three of these variables, cost of labor, cost of fuel and load factor, with the obvious purpose of determining the last two, viz., efficiency of operation and efficiency of original design.

Like all comparative analyses of costs and efficiencies the problem is one containing so many variables as to make difficult a mathematical solution, and it has often been questioned whether the generalized results obtained by such studies justify the elaborate processes involved.

Comparative costs of generating electrical energy are, however, becoming of increasing importance. The determination of reasonable rates by regulating commissions raises the question of relative efficiency. The value of a water power, where such a separate value exists, involves the question of the financial economy of hydraulic generation over other available processes, and while the present paper relates to steam plants only, similar methods must be developed for making such comparisons of various types of generation. Large operating syndicates are in need of concrete methods of analyses for comparing the results obtained by the various plants under their supervision. The necessity of a comprehensive scheme of analyses for these purposes will outweigh the limitations of comparative methods such as those outlined in the paper.

The classification of accounts which comprises the larger portion of the paper is not essential to the scheme of analysis outlined. Central stations are generally operating under classifications recommended by the National Electric Light Association. or the American Electric Railway Association or prescribed by state commissions. These accounting systems segregate the operating cost at switchboard from other operating costs and subdivide this general group into station labor fuel, miscellaneous operating expenses and maintenance items similar to those provided in the paper. While the proposed classification has many novel features it is not suited to all sized plants, does not take into account the possibility of the steam plant being used for other than steam generation purposes, evidently overlooks the impracticability of separately segregating general and undistributed expenses belonging to power costs from other portions of the business and introduces terminology much at variance with established practise. Present central station accounting methods have been gradually developed after years of experimentation and after consideration of the joint needs of the operating manager, the accountant and the engineer, and it is difficult to see what purpose will be accomplished by the changes contemplated. The accounts of any up-to-date electric utility permit separation into the items of Production Cost, Production Repair Cost and Investment Cost, the sum totals of which are used in the scheme of analysis, and will disclose the proportionate amount of expense burden applicable to these costs.

The most important feature of the plan outlined for compar-

ing costs is the load factor. The effect of load factor upon the investment costs is not difficult of determination since these costs per unit are an inverse function of the use. Question may be raised, however, as to the basis of calculating what the investment charges really are.

Interest and profit are inseparably associated in "rate of return" and few investors or bankers would finance a power plant with the expectation of receiving only a five per cent rate of return on their investment. It is true that money is often borrowed at five per cent interest for short terms or for long periods where the security is gilt edge, that is, with a substantial equity. The owners of the equity, however, expect larger rates of return than five per cent, either through the payment of interest or dividends or appreciation in market prices of their holdings. The use by engineers of low interest rates on the entire investment in calculating annual costs has contributed to the low regard in which capital "planted" is held today.

Considerable difficulty must necessarily be encountered when attempting to determine the proper amount to be set aside annually to cover that portion of investment charge represented by depreciation. The work of prophecy is an exceedingly difficult task at which to maintain a reputation for accuracy and has developed attractions since the world began. The man putting up his money cares little whether the unit of equipment requires abandonment on account of wearing out, obsolescence or inadequacy. He desires the engineer to advise him with respect to proper annual reserve which in the long run will reproduce his investment. Data upon which to predict such calculations are very meager and confined to a few instances, possibly not representative of the group or class. The accuracy of such calculations, even for a class, can not accordingly be very great, and herein lies another reason for estimating the cost of money at higher than ordinary interest rates, to at least in part compensate for the hazard arising out of the lack of knowledge of the probable life of units of equipment. The Institute has much work cut out for it along this line.

The effect of load factor upon the cost of operation and repairs is, however, more involved. This relationship, it is stated in the paper by the authors, may be expressed by the empirical formula

$$Y = s\frac{y\sqrt[4]{x}}{\sqrt[4]{X}}$$

where Y represents the cost in mills per kilowatt hour net output, X the corresponding load factor expressed in per cent, and y a constant for any curve. It is stated that "this law will hold between 15 per cent and 90 per cent load factors and is applicable for individual plants, but in comparing independent plants the cost of power in each plant should be reduced to a common load factor."

It would be fortunate if this important relationship could be thus simply expressed and the entire problem of station economy reduced to an approximate formula. It is observed, however, that the expression does not even generally fit the experience with which the writer is familiar. It does not account for variations in monthly costs with which the operator is interested and does not promise as great economies with better load factors as experience has proved are possible. Two typical instances, one condensing turbine operation and the other corliss condensing engines, may be cited as illustrations, and are given below:

Station A			Station B		
Monthly load factor.	Actual mills per sb. kw-hr.	Calculated mills per sb. kw-hr.	Monthly load factor.	Actual mills per sb. kw-hr.	Calculated mills per sb. kw-hr.
45	6.46	6.36	35	11.30	9.63
47	6.97	6.29	38	11.34	9.43
48	6.75	6.27	45	10.48	9.06
49	6.38	6.25	46	9.62	9.02
50	6.20	6.20	47	10.41	8.95
52	6.02	6.16	48	9.56	8.93
54	5.55	6.09	50	8.82	8.82
55	5.87	6.06	54	9.02	8.66
57	5.78	6.00			
60	5.42	5.93			

Station A is a medium-size plant of 30,000 kw. capacity. Station B is a small plant of 5500 kw. capacity. Both calculated costs are based upon the actual costs at a 50 per cent load factor. The choice of some other basis might have led to better closeness of fit of actual conditions and conditions assumed of formula, but would not have obviated the variations noted or spanned the maximum and minimum of the observed data.

An examination of the formula indicates why this is the case. The equation assumes a fixed relationship for all types of steam generation, makes no allowance for the operation of several units at different times or for the size of the equipment and its overload capacity. Assuming that the cost at 100 per cent load factor is unity, the formula fixes the cost at 20 per cent load factor at 1.47, a 50 per cent load factor at 1.19, a 60 per cent load factor at 1.14, etc. That important variations may be expected from the assumed standard is apparent from an inspection of the familiar economy curves of boilers, prime movers and generators. Various combinations of these factors are certain to effect changes in the resultant curve.

The cost sheet of the power plant at various load factors moreover, does not reflect merely the relation of input to output. It consists, especially in plants of limited capacity, of many items of cost fixed in their nature and independent of load factor or

output. Certain labor and maintenance items, for example may be expected to continue whether the plant is fully utilized or not. In small plants this constant quantity is of greater magnitude than in large plants and the effect on the cost at various loads is one of varying degree. All of these factors must be accounted for in any empirical formula designed to compare results of operation.

When the various items of power costs are separately scrutinized from month to month it is noted that each has its own basis of variation. Statistical units may be frequently developed to reduce these variables to more constant quantities and it is believed that this method of preserving data is the first step in the development of a cost formula. From a management standpoint increases in power costs are of particular interest because they are due partly to changes in the demand and load factor over which the management has little or no control and partly to direct additions to expense for which the responsibility can be directly localized. Both types of causes effect an increased cost per kilowatt-hour. The fuel cost which theoretically must be some function of the load factor will fall largely in the first class. The remaining items, labor, supplies, maintenance, etc., fall largely in the latter class and, while a small proportion of the total, is that part in which the greatest possibilities for economies in operation arise, and hence of the greatest interest.

A report form based upon a statistical comparison other than kilowatt-hour costs is used by one of the largest operating syndicates. The classification of accounts corresponds to that of the Public Service Commission of the state in which the plant is located. The data disclosed for the various items of steam and power plant costs are as follows:

STEAM GENERATION

No.	Account.	General Unit	Specific Unit
601	Boiler plant superintendence....................	sb. kw-hr.	Per cent. of 602-616
602	Boiler plant operating labor....................	"	Coal ton.
603	Coal and ash handling operating labor...........	"	Coal ton.
604	Water purification operating labor..............	"	100 cu.ft.
605	Fuel for steam (cost of fuel in storage)..........	"	Coal ton.
606	Water for steam.............................	"	100 cu.ft.
607	Water purification supplies.....................	"	100 cu.ft.
608	Boiler plant tools.............................	"	Boiler h.p-hrs.
609	Boiler plant supplies and expenses.............	"	Boiler h.p-hrs.
610	Removal of ashes expense (haulage from plant)..	"	Coal ton.
611	Maint. of boilers and boiler aux. equip. (labor)...	"	Boiler h.p-hrs.
612	Maint. of boilers and boiler aux. equip. (sundries).	"	Boiler h.p-hrs.
613	Maint. of coal and ash handling equip. (labor)....	"	Coal ton.
614	Maint. of coal and ash handling equip. (sundries).	"	Coal ton.
615	Maint. of water purification equip. (labor.).......	"	100 cu.ft.
616	Maint. of water purification equip. (sundries).....	"	100 cu.ft.
617	Maint. of boiler plant bldgs., fix. and grounds (labor)...................................	"	Boiler h.p-hrs.
618	Maint. boiler plant bldgs., fix. and grounds (sundries)....................................	"	Boiler h.p-hrs.

ELECTRICAL GENERATION

No.	Account.	General Unit	Specific Unit
626	Prime mover plant superintendence............	sb. kw-hr.	Per cent of 621-629. and 632-642.
627	Prime mover operating labor..................	"	kw. demand.
628	Prime mover plant elec. operating labor..........	"	kw. demand.
629	Prime mover plant mscl. operating labor.........	"	kw. demand.
630	Steam generated (proportion of cost) accts. 601-618	"	kw. demand.
631	Steam purchased..............................	"	kw. demand.
632	Prime mover plant lubricants..................	"	kw. demand.
633	Prime mover plant tools......................	"	kw. demand.
634	Prime mover plant supplies and expenses........	"	kw. demand.
635	Maint. of prime mover (labor).................	"	kw. demand.
636	Maint. of prime mover (sundries)...............	"	kw. demand.
637	Maint. of prime mover aux. equip. (labor).......	"	kw. demand.
638	Maint. of prime mover aux. equip. (sundries).....	"	kw. demand.
639	Maint. of generators and aux. gen. equip. (labor).	"	kw. demand.
640	Maint. of generators and aux. gen. equip.(sundries)	"	kw. demand.
641	Maint. of aux. electrical equip. (labor)...........	"	kw. demand.
642	Maint. of aux. electrical equip. (sundries)........	"	kw. demand.
643	Maint. of prime mover plant bldgs., fix. and grounds (labor)............................	"	kw. demand.
644	Maint. of prime mover plant bldgs., fix. and grounds (sundries)..........................	"	kw. demand.
731	Electric current exchanged (between plants)......	"	kw. demand.

For large plants these costs are subdivided in greater detail although the units of comparison are similar. The statements are also supplemented by statistics of demand, capacity, output, coal, water and lubricants. It will be noted that the electric generation costs are classified under both the kilowatt or demand unit and the kilowatt-hour or output unit. Some of these items vary directly with the demand; others respond to changes in output. The large majority of items, however, vary with the load factor and are affected by both demand and output. Were the plant operated at 100 per cent load factor by far the greater portion of the "steam generation" expense then would be an output cost. While operated at less than 100 per cent load factor standby losses are developed, a large portion of which are eliminated with better load factors. Labor costs develop even greater standby losses at low load factors, and these items alone serve to explain why better economies are possible, than the formula presented would anticipate.

The varying items comprising station operating cost are of too great importance to be merged into a general formula even when expressed as an equation of the fourth power, if the purpose in comparison for the sake of determining relative efficiency or possible future economy. If it is possible to develop a single formula which reflects in like manner two types of operation, it is believed that a segregation of the following four items is essential:

(a) Operating costs continuing irrespective of the output, such as labor, maintenance, etc., but affected by the demand.

(b) Costs varying as some function of the load factor, such as fuel, labor, water, etc.

(c) Costs varying directly with the output.

(d) Overhead costs such as supervision.

Such a separation will not only provide the means for direct comparison of different plants but will give the separation of costs necessary to determine the charge to be borne by various services supplied by the same central station, such as traction and commercial lighting, and will serve as a basis for fixing the rate of charge to be made to customers under a demand and energy schedule. It also does not seem probable that fullest economy can be obtained in operation until those portions of cost which directly concern the management are separated from those costs which are dependent upon a varying public demand for service and hence without the control of the management.

S. D. Sprong (by letter): The following notes refer only to the paragraph entitled "Estimated Life of Apparatus", including Life Expectancy Table, of the paper by Messrs. H. G. Stott and W. S. Gorsuch.

I agree with the writer that estimating the life of apparatus is a highly speculative matter, but do not believe that all the figures given in the life expectancy table represent the results which have been obtained in first-class well designed power plants.

Between the years 1893 and 1898, a number of first-class steam-driven power plants were designed or erected in the greater city of New York. These plants were equipped with reciprocating engines, the majority of which are still in operation and apparently will continue to operate for years to come. It, therefore, seems that the total life of twelve years estimated for engines and condensers is far below what may actually be obtained in view of the number of engines now operating which are from 15 to 20 years of age. The same general statements apply to alternators for which the estimated life is stated as twelve years, as practically all the large alternators installed in New York City beginning with 1897, or sixteen years ago, are still in operation.

Synchronous converters are given an estimated life of twenty years. A number of these machines have been in operation in New York City from about the year 1894, and a large number of the batteries now in use have been in service from 10 to 15 years. The author estimates ten years as the average life of the battery, but there are a large number of batteries now operating in New York considerably older than this, and which batteries are still in first class condition. In the early days the battery manufacturers were willing to guarantee the total maintenance of the battery for 6 per cent of the cost which, without considering interest, would mean a life of over sixteen years. The actual scrap value of lead in batteries will run from 10 per cent to 20 per cent of the original cost, according to the condition of the

plates. The average life of a battery depends almost entirely upon its number of discharges rather than its life in years. The vehicle battery may have to be replaced yearly if discharged daily, whereas a station battery under average operating conditions would probably not have the same number of discharges in thirty years.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 26, 1913.

AUTOMATIC SUBSTATIONS

BY H. R. SUMMERHAYES

The object of this paper is to describe the automatic substation at Detroit, in which there is working a synchronous converter controlled entirely from a distant station; some observations are made also on automatic substations in general.

While many motors of all sizes operate without attendance, and with little attention, practise has always required operators at converter substations. In earlier days the operators were necessary, but the converter is now such a reliable piece of apparatus that in some cases operators are not required, as in the station described in this paper.

Automatic Operation. Automatic operation, strictly defined, is that in which a machine performs its functions without any human control; in the Detroit station the control is from a distance but the apparatus may be said to be automatic, inasmuch as the various functions of starting, stopping and regulation are performed without the supervision of an attendant in the station where the machine is located.

The operation without an attendant of a commutating machine of fairly large size in a substation, supplying current to a commercial lighting system, is an idea so different from the generally accepted practise that to lead up to it some consideration will be given to more familiar examples of automatic substations.

Remote-controlled electrical apparatus is now widely used for a variety of different purposes. It is generally used for the reason that the machine to be controlled is so located as to be inaccessible, or for reasons of convenience, to save labor, or to concentrate at one point the control of a number of machines whose functions are related.

When the motor is inaccessible, either by reason of its location or being enclosed, or when it is out of sight and hearing of the operator, it does not matter whether the motor is in the next room or a mile away. It is only a question of degree.

The following are some of the more familiar examples of remote control. In some of these the machines which are operated by the electric control are visible to the operator and in other cases he receives signals, that the machine has operated, but in nearly all cases the electric motor is out of sight and receives only occasional attention and inspection.

Train Lighting. In systems of train lighting with an axle-driven generator, the generator itself is inaccessible and out of sight and receives only occasional attention. Its operation as to commutation, temperature rise, etc., is taken for granted and the control is usually by four automatic devices, *i.e.*,

1. A pole changer which reverses the polarity of the generator when the direction of motion of the car is reversed.

2. An automatic switch which keeps the generator disconnected from the system at low train speeds and connects it when a certain speed is reached.

3. A current regulator which varies the generator field so as to supply a constant current to the storage battery.

4. A lamp voltage regulator which operates usually by working on a variable resistance in the lamp circuit.

In the case of train lighting the generator is so inaccessible that it might as well be a mile away.

Transformer Substations. The transformer substation, whether out of doors or indoors, is one of the most familiar examples of operation of electrical apparatus without an attendant. Of course, the transformer is a piece of stationary apparatus, but even a transformer shares with moving machinery the possibility of injury by lightning or overload.

Regulators. It is not unusual practise for lighting companies supplying alternating current to install automatic feeder regulators in a transformer substation without an attendant and with only occasional inspection. Here we have a transformer with the addition of an intermittently moving machine. Small regulators are now built of the pole line type designed to be mounted outdoors on a pole and to operate continuously and automatically with very infrequent inspection. These regulators contain a continuously rotating motor.

Blower Motors and Pump Motors. These motors are frequently

located in inaccessible places and receive scant attention as to operation. They are started from a distance and are depended upon to give good commutation and to operate without undue heating or bearing trouble. They are frequently controlled by automatic pressure regulators or float switches, and may be located at a distance, so that the only indication the operator has of their having started is the current in his ammeter.

Transportation. A very large class of remote-controlled apparatus is used for various kinds of transportation, such as electric street railways, electric trains, elevators, cranes, ore-loading machinery, mine hoists, electric ship propulsion, etc. In all of these, the electric motor is remote from the operator and receives only periodical inspection. Its operation is taken for granted, but in most cases the operator sees the movement of the machinery driven and regulates the control accordingly. In case of large mine hoists, the hoist may be out of sight of the operator and he has merely an indicator showing its movements.

Lighting of Isolated Buildings. There are a good many installations for lighting of large residences, hotels, etc., in the country, consisting of a storage battery and generator and an internal combustion engine, which may be said to be examples of automatic substations, as in some of these installations arrangements are made so that the voltage of the storage battery is allowed to vary between narrow limits, the engine and generator being automatically started up at the lower limit and when the storage battery is charged to the higher limit the generator and engine are stopped. These installations do not require any attention so far as the generator is concerned, excepting the occasional inspection.

Further Applications. With these examples in mind in which electric motors, remotely controlled and operated practically without attendants, are used in sizes from a fraction of a horse power up to thousands of horse power, many of these motors being of the commutating type, and also considering the instances in which small commutating, direct-current generators are used, it is only a step further to apply the same principles to a generating station or a substation.

Induction Generator. It is planned to install on a hydroelectric system in the West, an induction generator of about 1400 kw. capacity located in a station, without an attendant, several miles from the main hydroelectric generating station of the same company. This machine, after being started up

by an operator sent over for the purpose, will operate without any hydraulic governor, the waterwheel working at full gate all the time. While connected to the line, it will receive its magnetizing current from the synchronous generators in the other station and will deliver its full load into the system at all times when the load exceeds the rating of this induction generator. The frequency and speed will be controlled by the waterwheel governors at the main station in which most of the generators are of the larger capacity.

At times when the total load becomes less than the capacity of this machine, it will be disconnected by the operator at the main station opening the switch on the line leading to the induction generator. This generator will then run at nearly double speed and will be allowed to do so until again required, when an operator will be sent over to slow down the induction generator to a point approximating synchronism, when it may be thrown on the circuit again. It will, of course, be designed to run safely at double speed for any length of time, but in case of the machine not being required for a long period an operator would be sent over to shut it down.

It would be possible by the use of three or four control wires and a motor operated hydraulic governor to start up and shut down this machine from the main station, in which case the only attention required would be daily inspection and oiling of the hydraulic governor and such parts of the waterwheel as require oil. This installation is, of course, much simplified by not having any exciter. As at present planned, it is also much simplified by not having any hydraulic governor, so that the only moving parts in the station are the rotors of the waterwheel and generator which are on the same shaft and the only bearings are the thrust and steady bearings, which are lubricated by a simple oil pumping system in operation whenever the induction machine is running.

This induction generator, being rather slow speed and operating at 60 cycles, has a power factor of about 80 per cent. If the head permitted a high-speed generator, the power factor could be made much better.

It is worthy of note that this installation is on the same stream as the main plant but located above it, and will use the same water. The only governor will be an emergency over-speed trip which will not shut down the waterwheel but will simply disconnect the induction generator from the line in the event

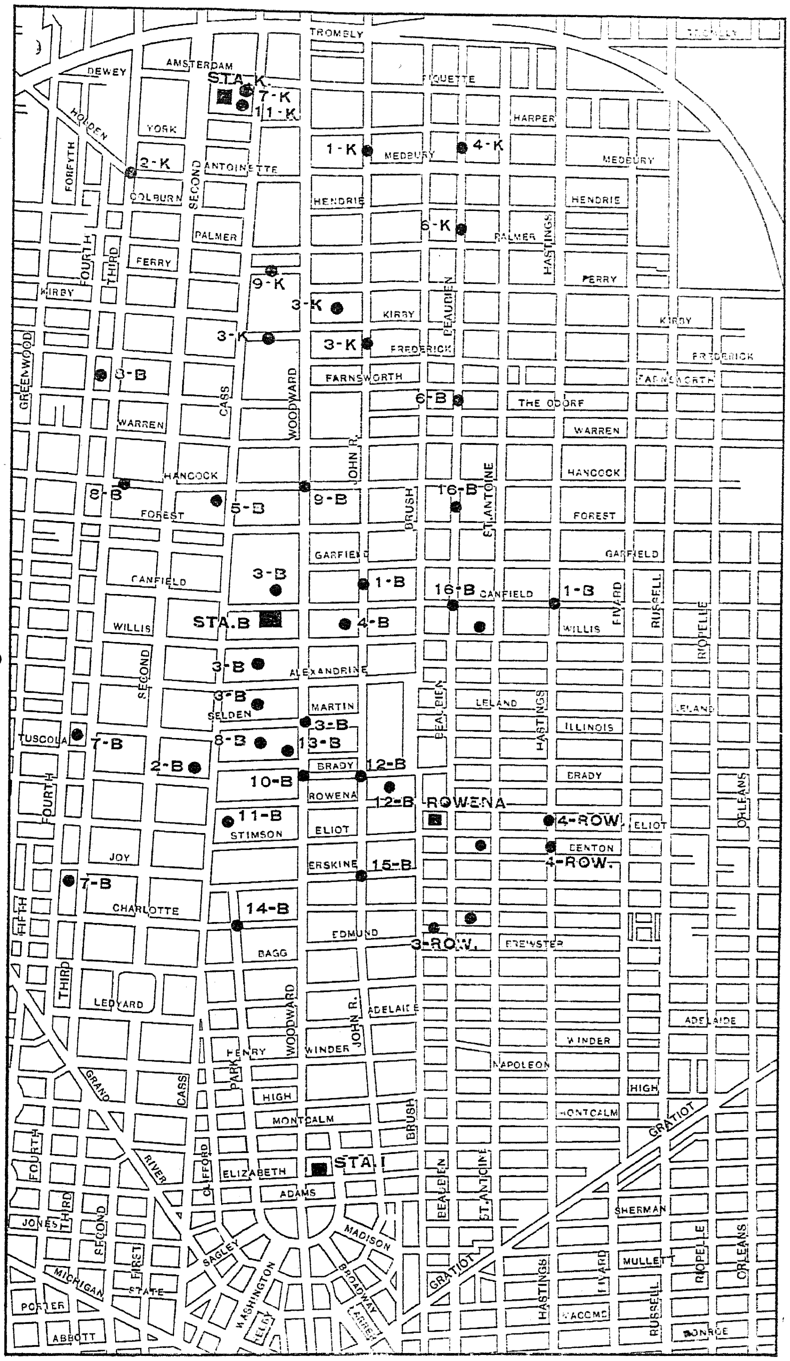


FIG. 1

■ Station ● Feeding point.

of a sudden interruption of load on the main line, which would otherwise permit the induction generator to speed up and drag the rest of the machines along with it.

Synchronous Converter. The Edison Illuminating Company of Detroit has installed a synchronous converter with special automatic switchboard equipment, arranged so that the converter can be started, controlled and stopped, from a distant point, without any control wires.

The synchronous converter, transformers and part of the switching appliances are located at the Rowena Street substation, about one mile from the center of the Edison three-wire network and about one mile from Station I, whence the equipment is controlled. Station I is one of the largest substations on the Edison system at Detroit. See map, Fig. 1.

Purpose of Installation. The load on that part of the Edison three-wire network near Rowena St. station, located in one of the residence sections of Detroit, has been increasing so rapidly that the illuminating company was faced by the alternative of installing more feeder copper or a new substation in order to keep the service in this section up to standard. Either of these alternatives involved considerable expense, compared to the revenue from the section in question, and it was, therefore, decided—in order to keep up the voltage on this part of the system—to install a 500-kw. synchronous converter in a substation without an attendant and make arrangements so that the converter could be started, stopped and its voltage and load controlled from Station I a mile away; also so that the machine would be automatically protected in case of disturbances on the system or accidents to the machine itself.

This problem was presented to the engineers of the manufacturing company, the illuminating company stipulating that there should be no control wires, the only conductors extending between the stations being those of the triple-conductor cable carrying the primary current at 4400 volts, three-phase, from Substation I to the Rowena Street station.

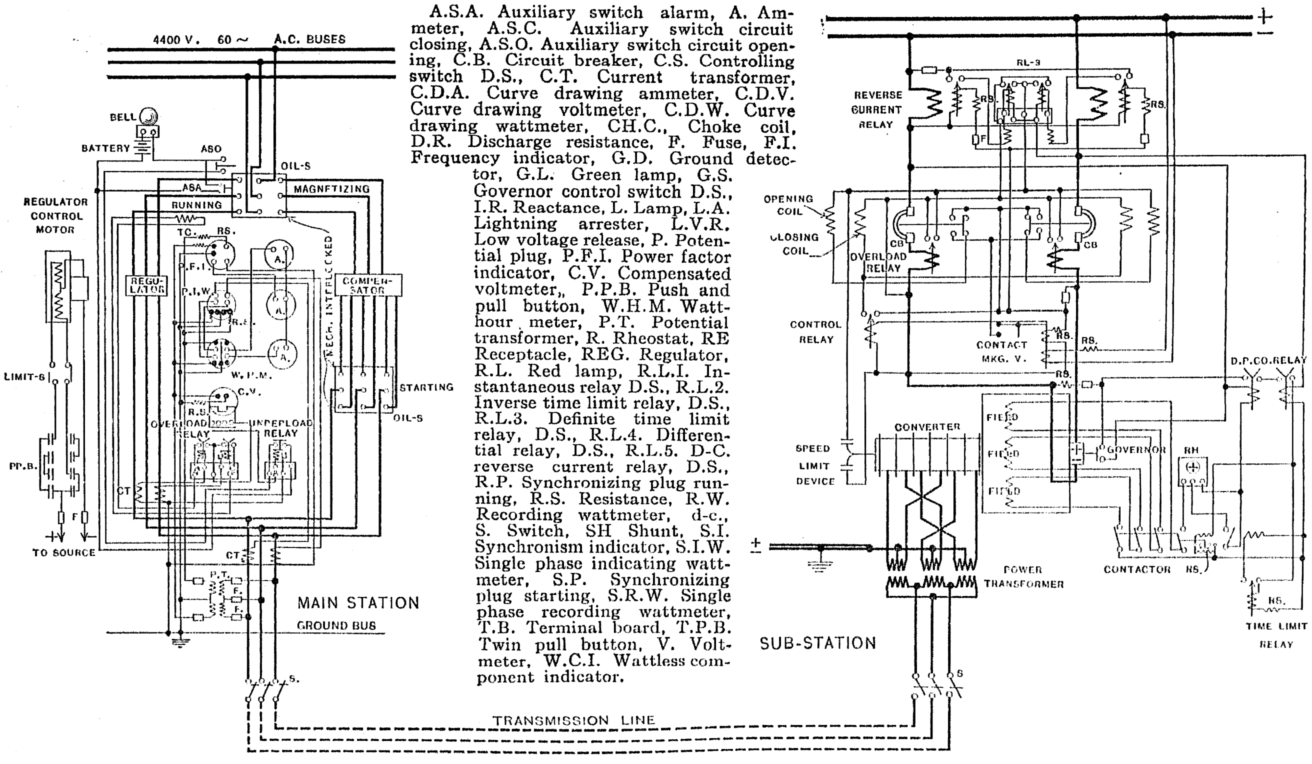
The connections are shown on the diagram, Fig. 2.

Voltage Rating and List of Apparatus. The supply of electricity of substation I is 4400 volts, 60 cycles, three-phase.

The apparatus located at this station consists of the following:

One 4400-volt, three-phase starting compensator with $\frac{1}{3}$, $\frac{2}{3}$ and full voltage taps.

One 4400-volt, three-phase induction regulator with a total



A.S.A. Auxiliary switch alarm, A. Ammeter, A.S.C. Auxiliary switch circuit closing, A.S.O. Auxiliary switch circuit opening, C.B. Circuit breaker, C.S. Controlling switch D.S., C.T. Current transformer, C.D.A. Curve drawing ammeter, C.D.V. Curve drawing voltmeter, C.D.W. Curve drawing wattmeter, CH.C., Choke coil, D.R. Discharge resistance, F. Fuse, F.I. Frequency indicator, G.D. Ground detector, G.L. Green lamp, G.S. Governor control switch D.S., I.R. Reactance, L. Lamp, L.A. Lightning arrester, L.V.R. Low voltage release, P. Potential plug, P.F.I. Power factor indicator, C.V. Compensated voltmeter,, P.P.B. Push and pull button, W.H.M. Watthour meter, P.T. Potential transformer, R. Rheostat, RE Receptacle, REG. Regulator, R.L. Red lamp, R.L.I. Instantaneous relay D.S., R.L.2. Inverse time limit relay, D.S., R.L.3. Definite time limit relay, D.S., R.L.4. Differential relay, D.S., R.L.5. D-C. reverse current relay, D.S., R.P. Synchronizing plug running, R.S. Resistance, R.W. Recording wattmeter, d-c., S. Switch, SH Shunt, S.I. Synchronism indicator, S.I.W. Single phase indicating wattmeter, S.P. Synchronizing plug starting, S.R.W. Single phase recording wattmeter, T.B. Terminal board, T.P.B. Twin pull button, V. Voltmeter, W.C.I. Wattless component indicator.

Fig. 2—Diagram of Connections

range of 20 per cent in voltage. The regulator is connected in series with the running switch and is not in circuit when starting. Fig. 3 shows this regulator.

Four hand-operated oil switches on the switchboard, of which No. 1 is a magnetizing switch, No. 2 and No. 3 tap switches for use with the compensator, and No. 4 a running switch.

Three a-c. ammeters.

One power factor indicator.

One polyphase indicating wattmeter.

One watt-hour meter.

One compensated voltmeter to read the voltage at Rowena Street. Necessary current and potential transformers.

One underload relay and bell alarm.

One inverse time limit overload relay. The overload relay operates the running switch.

The material of the switchboard is pink Tennessee marble. (See Fig. 4).

The only connection between substation I and the Rowena Street substation where the converter is located, is the three-conductor 4400-volt cable which carries the main current, and there are no auxiliary control wires between stations.

Rowena Street Substation. At this station are located the synchronous converter, which is a six-phase converter, 12 poles, 500 kw., 600 rev. per min., 250–300 volt d-c., three transformers, each 175 kv-a., rated 4400—205 volts, oil-cooled, and the automatic control apparatus consisting of the following:

Two 3000-ampere solenoid-operated main circuit breakers with overload trip.

Two reverse-current relays for above.

One solenoid-control relay used in connection with the circuit breakers.

One differential contact-making voltmeter.

One four-pole field contactor. (The field is broken at several points, on account of the high induced voltage at starting.)

One single-pole field contactor, with time limit relay.

One field rheostat.

One double-pole relay for protection of field circuit.

One centrifugal switch or governor mounted on shaft of synchronous converter.

Fig. 5 is a view showing the exterior of Rowena St. substation, which is built without windows to prevent noise being heard outside of station. Ventilation is through baffled openings in side and roof.

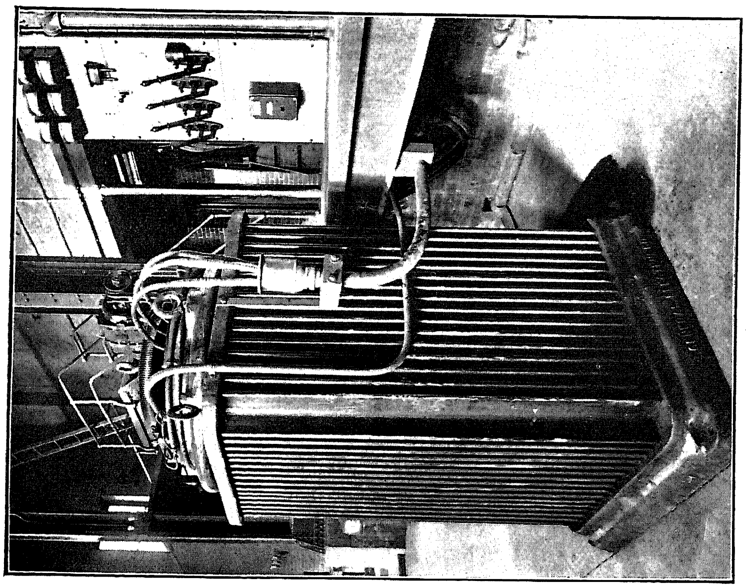


FIG. 3

[SUMMERHAYES]

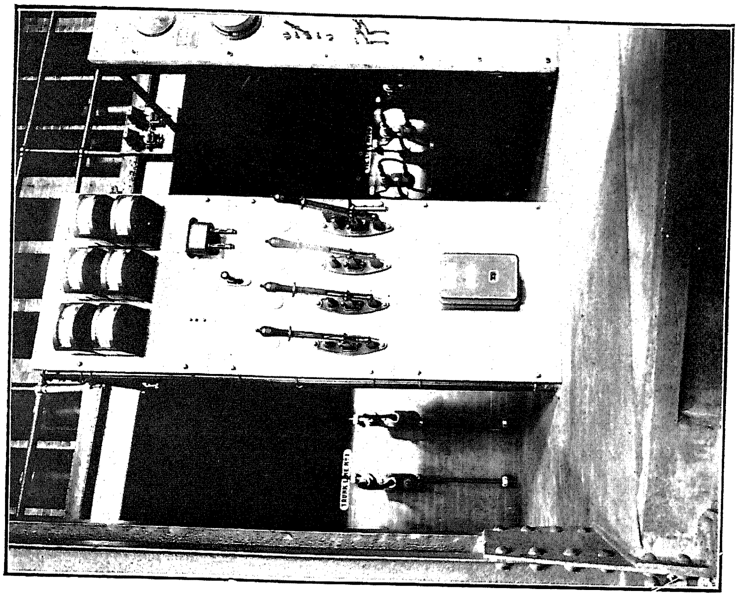


FIG. 4

[SUMMERHAYES]

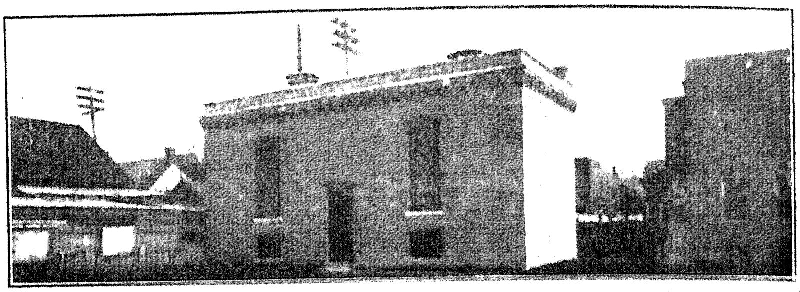


FIG. 5 [SUMMERHAYES]

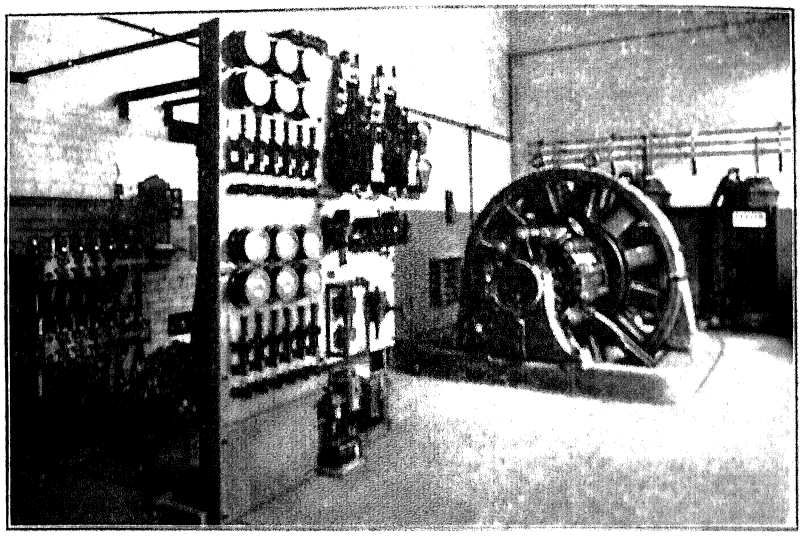


FIG. 6 [SUMMERHAYES]

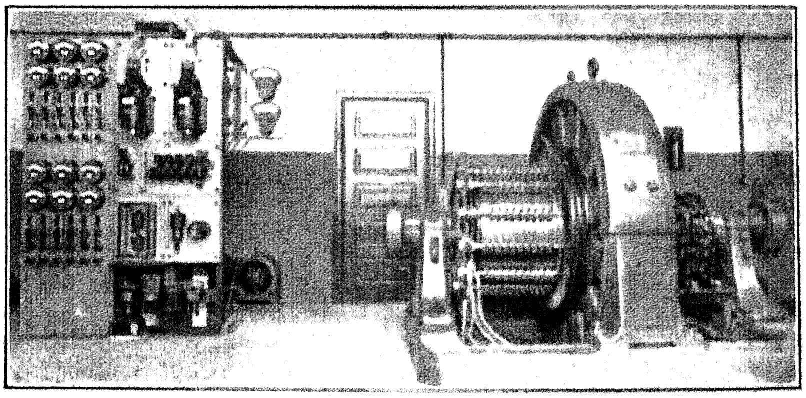


FIG. 7 [SUMMERHAYES]

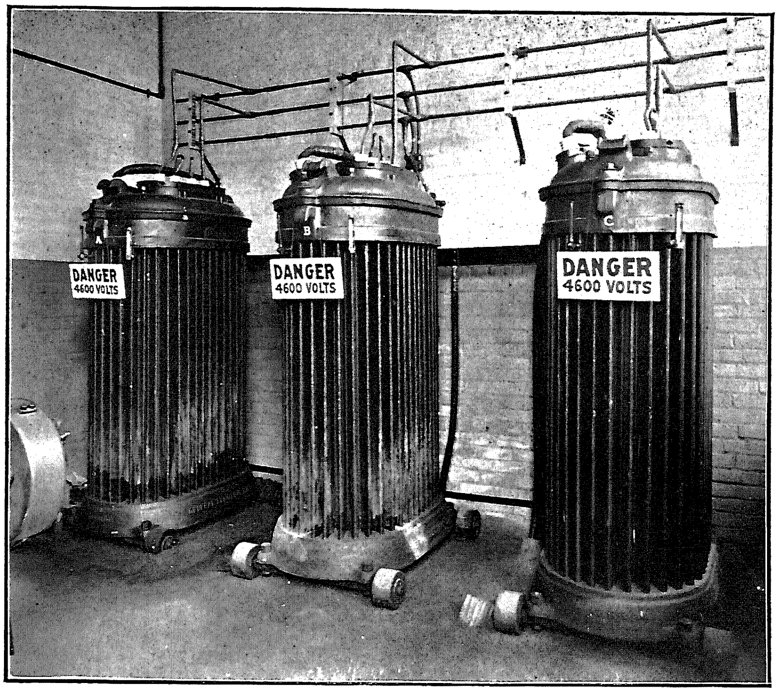


FIG. 8 [SUMMERHAYES]

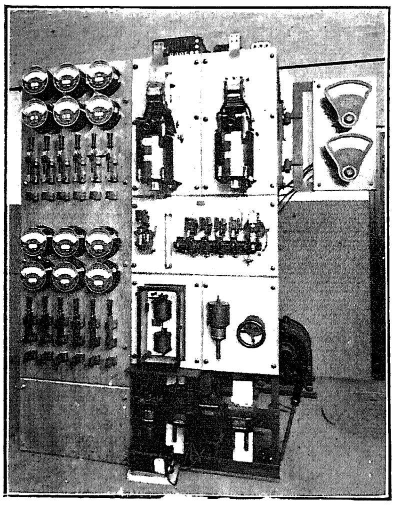


FIG. 9 [SUMMERHAYES]

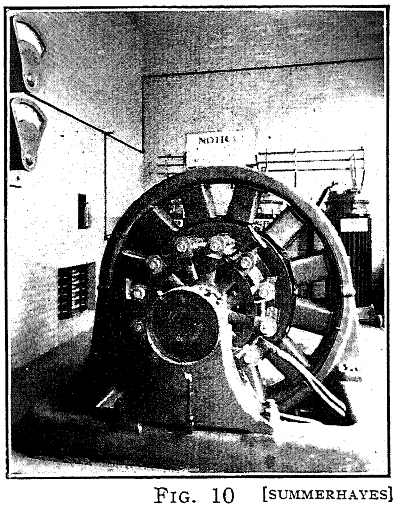


FIG. 10 [SUMMERHAYES]

Fig. 6 is a general view of the interior, Fig. 7 shows the converter and switchboard, and Fig. 8 shows the transformers, also the end of the converter shaft with speed limit switch.

Fig. 9 is a front view of switchboard showing the automatic control device at right and feeder panel at the left, and Fig. 10 is an end view of the converter showing the centrifugal governor or field switch.

All of the devices of the control equipment, excepting the field rheostat and governor, are mounted on two pink Tennessee marble panels.

The circuit breakers are supplied with sockets and auxiliary handle so that they may be worked by hand.

A number of feeders connected to different points on the 125-250-volt Edison three-wire system in this vicinity are brought into the Rowena Street substation and the feeder switches are normally left closed so that there is 250 volts on the bus in this station available to operate the contactors which close the field when the control circuit of these contactors is closed by the governor.

Operation

Starting. In order to start up the converter, the operator at substation I proceeds as follows:

First: The induction regulator is set at maximum lowering position.

Second: The magnetizing switch is closed.

Third: The $\frac{1}{3}$ tap switch is closed, throwing $\frac{1}{3}$ voltage on the line leading to the Rowena Street substation. The converter starts on this tap and reaches synchronism in 20 or 30 seconds. Just before the converter reaches synchronism (that is, within 5 per cent of synchronism), the governor on its shaft closes the control circuit of the field contactors and the four-pole contactor operates immediately, exciting the rotary converter field from the bus so as to give it the correct polarity, but with a considerable resistance in series with the field. As soon as this weak field is thrown on, the rotary converter pulls into synchronism with the proper polarity but at $\frac{1}{3}$ voltage. This operation is made evident to the operator at I street by watching his a-c. ammeter, on which the current decreases from the initial starting current to about $\frac{1}{2}$, and suddenly increases as the field is automatically applied, then settles to a low and steady value as the converter falls into synchronism.

Fourth: Just after the automatic application of the field, the operator opens the $\frac{1}{3}$ tap switch and closes the $\frac{2}{3}$ tap switch.

Fifth: The operator then opens the $\frac{2}{3}$ tap switch and closes the running switch. After the closing of this switch the converter is in synchronism but operating at a low d-c. voltage on account of the position of the induction regulator and operating with a very weak field. On account of the weak field, the power factor at this time will be lagging.

Sixth: Within a few seconds the second field contactor automatically operates, cutting out sufficient field rheostat so as to give the rotary full normal field current. The control circuit of this contactor was closed by the governor at the same time as the other contactor, but its operation was delayed by a time limit relay. The operation of this contactor is immediately evident to the operator at Station I by the increase in current on the a-c. ammeter and the changing of the power factor from lagging to leading.

Seventh: At this point the converter is running in synchronism with full field and correct polarity and all ready to be connected to the direct-current buses, excepting that its voltage is low, owing to the position of the induction regulator. The operator now brings up the voltage by the induction regulator and at the moment the voltage across the brushes of the converter exceeds by a very small percentage the voltage on the buses, the contact making voltmeter operates. This device is differentially wound, one coil connected to the buses and the other to the brushes of the converter. The bus voltage may vary at different times of day from 250 to 300 but whatever voltage is across the buses, this differential device acts only when the synchronous converter voltage exceeds the bus voltage by a small percentage. This device makes a circuit through the control relay which operates the closing coils of the two main circuit breakers and connects the synchronous converter to the busbars. This action is so accurate that the converter may be made to take any percentage of load that is required. Ordinarily it is so adjusted that when the circuit breakers close, the converter takes about one-tenth load.

Load Control, Etc. The voltage at points on the Edison three-wire system in the neighborhood of the Rowena Street station is observed at Station I by means of the pressure wires ordinarily used on these Edison systems and the amount of load taken by the converter at Rowena Street is changed by the operator to meet the voltage conditions on the system. The change in load is effected by manipulating the induction regulator.

The amount of load at any time is indicated by the a-c.

ammeters in connection with the indicating wattmeter and the power factor meter.

Stopping. In order to stop the synchronous converter, the running switch at Substation I is opened. This disconnects the a-c. supply and leaves the synchronous converter running as a d-c. motor. The reverse-current relays are set so that they will operate on the current which the converter takes as a d-c. motor and their operation opens the main circuit breakers and disconnects the converter from the d-c. busbars and, as the converter slows down, the governor resumes its starting position and the field contactors open so that everything is ready for a new start.

Protection. In case of a short circuit on the a-c. system at some point between the main station and the switchboard at Station I, the d-c. current feeding back from the d-c. systems through the synchronous converter operates the reverse-current relays and opens the solenoid circuit breakers so that the converter is left connected to the a-c. system. When the a-c. short circuit disappears and the a-c. voltage comes up again to normal the converter is automatically connected in the d-c. system again, unless the current required to synchronize the converter is heavy enough to open the main switch at Station I by means of the overload relay, in which case the converter may be synchronized by the magnetizing and tap switches, as explained under "Starting."

In case of a short circuit on the a-c. circuit or on the cable between Station I and Rowena Street, or in the armature, transformers or regulator, the direct current feeding through the converter into the short circuit operates the reverse-current relays and opens the solenoid circuit breakers, and the alternating current feeding into the short circuit operates the overload relay and opens the main switch at Station I, disconnecting the converter from the line. With the original equipment, time limit attachments were added to the reverse-current relays so that they would not operate in case of mere momentary surges. These relays are not being used in the actual operation of the equipment as they are considered unnecessary by the illuminating company. Two reverse-current relays are used so that safety is assured. If both should fail, the speed-limiting device and the overload coil are both available to open the d-c. circuit breakers.

In case of a short circuit on the d-c. side, the overload relay at Station I will open the running switch and the converter will

be disconnected as in the ordinary operation of shutting down. If this d-c. short circuit is a very severe one, the overload trip coils of the circuit breakers which are set rather high will also operate.

The field circuit of the synchronous converter is protected by means of a double-pole overload relay. The shut-down of the converter from any cause is indicated by the underload relay at Substation I.

This station has been operated ever since it started without any regular attendant, but since the equipment was novel, for the first few weeks it was the practise to send a man over from Substation I to watch the operation when the outfit was being started and in this way several points have been observed which have enabled us to perfect the equipment.

The centrifugal switch originally used to close the field circuit was found to be unsuitable, and this has been replaced by one of different design, which is reliable and has given satisfaction. During the few days the first switch was out of service, the field contactor circuit was closed by hand when the machine was being started. Shortly after installation there were two or three cases when the machine failed to start; such failures have now been eliminated by proper adjustment and minor changes in the relays. It is the intention to have this equipment inspected once a day.

The illuminating company may decide later to put in a thermostat on the bearings, recording through a telephone wire to Substation I, so as to eliminate danger from this source, but it is not believed this will be necessary.

The bearings are of the ring oiling type generally used on machines of this class, so that very little trouble may be expected.

In addition to the governor used for closing the field circuit, the synchronous converter is equipped with the usual centrifugal speed limit device.

The illuminating company expects to extend this remote control system to other substations.

Fire Risk. The fire risk is practically nil, except for the chance of the windings of the machine taking fire from an accidental burn-out. This may be minimized by automatic extinguishers. It would not be possible to use automatic sprinklers in a cold climate unless the substations were heated, but some automatic extinguisher, using Pyrene or similar liquid freezing at a lower temperature, may be devised, and this would be preferable to water for other reasons as well.

Other Applications. In the station described, the converter is of the type without commutating poles. An automatic installation including a commutating-pole converter, would require a solenoid mechanism for raising the brushes when the field contactors open while the machine is shutting down, the same mechanism to lower the brushes when the machine has started and reached synchronism. This would be worked by the closing of the field contactors.

When an automatic substation is installed on an Edison system the field contactors may be operated from the 250-volt bus, connected to the system outside, and it may be assumed there is always voltage on this system.

In case of an automatic substation on an electric railway system, it may be desired to start up the station when there is no voltage on the trolley wire. In such a case the machine may come up to speed with the wrong polarity, since there is no means of determining the polarity by exciting the field from the trolley. To meet this requirement, a special relay, devised by Mr. J. B. Taylor, or a storage battery, may be used. Since railway substations are generally located on the line of the railway, it is frequently found convenient to combine the substation with a waiting room and ticket office, so that the operator performs both functions. Where it is not necessary to do this the automatic substation may be used.

Still another application of these principles may be to simplify the control of machines in a large station containing several converters. That is to say, the low-tension switches near the machine will be eliminated and one operator at the switchboard would take care of the entire starting.

While the automatic starting of this converter as described in detail may seem complicated, in actual practise it is very simple, as it merely requires the operator to close four oil switches in rotation, 1, 2, 3, 4, and to manipulate an induction regulator, the machine being thrown on the system with very little disturbance.

Conclusion. The remote control of synchronous converters enables a plant operating the Edison three-wire system to extend the economical limits of the system, since the cost of the labor of station operators and the cost of heating the building forms a large proportion of the running expense of a substation. With the station heating expense and the regular watch of station operators eliminated and the labor expense limited to

the cost of daily inspection, it becomes possible to operate substations where previously the density of the load would not warrant a substation.

In general, this means that the Edison three-wire system in a city may economically be extended to cover a greater territory than at present. It will be possible to reduce the investment in feeder copper by using smaller substations set closer together.

Acknowledgment is made to Mr. G. W. Cato, of the Edison Illuminating Company of Detroit, for information and illustrations used in this paper.

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CONVERTING SUBSTATIONS IN BASEMENTS AND SUB-BASEMENTS

BY B. G. JAMIESON

The type of substation discussed in this paper is that which is located below street grade in commercial buildings of large cities. Sub-grade at once suggests valuable real estate, crowded quarters flooded basements, ventilating difficulties and machinery handling problems. Coupled with these disadvantages and risks are certain economies and other features which have made these substations a matter of much importance in our largest cities. The purpose of this paper is to show the influence of these factors upon the apparatus and arrangement of this type of substation.

In the down-town district of Chicago, for example, the development of converting substations below street level has covered a period of approximately fifteen years and in that time the capacity of single converting units has increased from 250 kw. to 3500 kw., and fortunately the building art has so advanced that head-room of from 15 to 26 ft. (4.5 to 7.9 m.) has been made available in some of the sites more recently secured. In the heart of Chicago, practically within the "loop," there are ten substations either in service or about to be commissioned which have a combined capacity of 42,000 kw. in converting apparatus or storage batteries, all operating on the Edison three-wire system, eight of which, with a total capacity of 29,000 kw., are of this sub-grade type. One of the latest substations has an ultimate capacity of four 3500-kw. and one 2000-kw. synchronous converters; one of the earliest has eight 500-kw. and four 1000-kw. converters. The district has an area of only 0.81 sq. mi. (2.1 sq. km.) and a connected load of 1,940,000 lamps (50-watt equivalent), a maximum last year of 31,000 kw. and an annual

load factor of 32 per cent. Fig. 1 shows the 24-hour load on the day of maximum kw. in the winter of 1912, and Table I shows the annual kw. increment, an interesting table, in which may be discerned indiscriminate periods of great business expansion and depression and, faintly, the advent of the tungsten lamp.

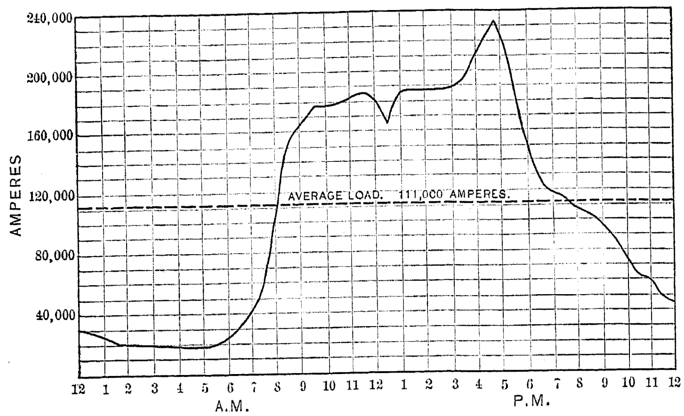


FIG. 1—LOW-TENSION DOWN-TOWN DIRECT-CURRENT LOAD ON DAY OF MAXIMUM OUTPUT—DEC. 16, 1912

Devoid of all exterior attractiveness, these converting sub-stations may be viewed from the engineer's standpoint as a series of large, deep pits surrounded by concrete walls, upon which devolves the duty of resisting the inward thrust of the

TABLE I

PER CENT OF INCREASE OF DOWN-TOWN LOW-TENSION MAXIMUM LOAD

	Per cent
1901 over 1900	15.5 increase.
1902 " 1901	25.7 "
1903 " 1902	18.5 "
1904 " 1903	5.5 "
1905 " 1904	27.4 "
1906 " 1905	5.4 "
1907 " 1906	7.8 "
1908 " 1907	3.0 "
1909 " 1908	10.0 "
1910 " 1909	1.7 decrease
1911 " 1910	6.4 increase
1912 " 1911	4.8 "
1913 " 1912	7.0 increase (estimated)

abutting earth and of keeping out the surface and sub-soil water, bottomed with a layer of concrete which must be heavy enough to keep the earth from crowding up into the pit, and intersected vertically by numerous columns which keep

thousands of tons of steel, concrete, and tile from falling into it. Occasionally a group of fire engines may pour or a broken street main may liberate perhaps 10,000 gal. (37,854 l.) of water per minute directly over the roof of the pit, which has two open stair wells, a shaft of approximately 175 sq. ft. (16.2 sq. m.) to admit apparatus, and air ducts of 50 sq. ft. (4.6 sq. m.) section; and with all this the converters must operate continuously. Quite different from the super-grade structure, the comparatively simple duty of which is to protect the apparatus from the weather.

The sub-grade substations may be grouped in two classes, I—the basement type, and II—the sub-basement type, the distinguishing feature being that Class I usually includes the sub-sidewalk space and may be reached directly from the street or sidewalk level; whereas Class II may be either a first or second

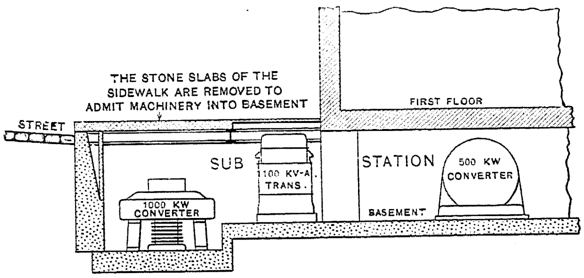


FIG. 2—SECTIONAL ELEVATION, BASEMENT TYPE

sub-basement of a twenty-story building, which is isolated from both street and sidewalk. Figs. 2 and 3 show the conventional forms of entrances to these two types.

Class I typifies the earlier stage of the development when basement space was not so valuable as now and in many ways presented proportionately as great construction problems as Class II, for, even though the depth was not so great, the adaptation of a given space for an electrical substation had to be carried out at the foundations of a high building designed without thought of such purpose.

In contrast to the ordinary super-grade substation there is no convenient 12- or 14-ft. (3.6- or 4.3-m.) doorway, with a crane just inside for admitting and handling a 7000-lb. (3175-kg.) transformer. The roof of the substation is on the level of the sidewalk and the space above the roof is another's premises. Access must be had through the sidewalk or adjacent alley.

The Class I machinery entrances are usually simply sidewalk slabs, the removal of which gives a clear opening into the substation, while Class II intakes may be expensive shafts with offsets, totaling 40 ft. (12.2 m.) in depth. Fig. 6 shows the method of lowering a 3850-kv-a. transformer through a Class II entrance. Work of this sort is exceedingly precarious and requires the utmost caution on the part of the engineer in charge, for the shifting of centers of gravity with respect to points of support, and of the points of maximum bearing pressure, are made rapidly and in a manner often not contemplated in the

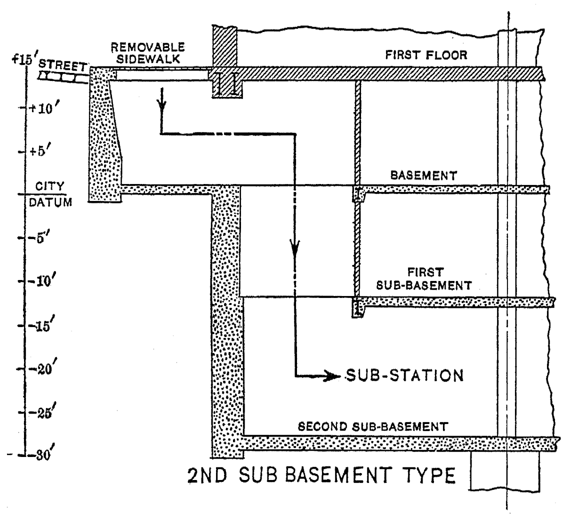


FIG. 3 —SECTIONAL ELEVATION, SECOND SUB-BASEMENT TYPE

design of apparatus. Clearances of an inch (25.4 mm.) or less are common in this class of work.

In the utilization of this entrance many untoward factors materialize. In a crowded business street only a limited time is allowed at the week-end, seldom exceeding thirty consecutive hours, in which sidewalk slabs must be removed, the machinery put in the substation space and the sidewalk slabs put back into original position. This usually means night and Sunday work to be carried out regardless of weather conditions. The effect of this close work may be reflected as far back as the factory from which shipment of apparatus is made. To illustrate—a 3500-kw. synchronous converter with its appurtenances, a gross weight of 135 tons, must be brought into the substation on a certain

date. Factory shipment is scheduled accordingly, allowing for the vicissitudes of railway transportation, so that demurrage may be avoided. The apparatus must be especially cribbed to fit the entrance to substation, or perhaps only partially assembled or so arranged on the cars that proper order of removal may be followed; perhaps a particular 15-ton piece has to be placed on the wagon in a certain manner because it is not possible to reverse its position after loading.

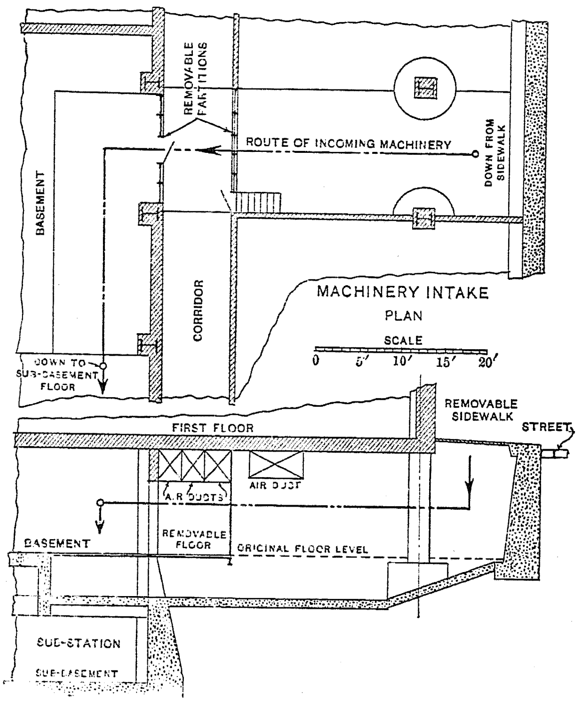


FIG. 6—PLAN AND SECTIONAL ELEVATION OF MACHINERY INTAKE

In the Class I substations, there is naturally more latitude in the choice of location for this entrance than in Class II, and consequently the work is generally less difficult. The parts to be handled are usually smaller in Class I substations, so that Class II machinery handling problems are much more serious. For instance, one substation has a machinery intake in the exact form shown in Fig. 3, the course of incoming machinery being indicated by dotted line. The apparatus may be 10-ft. (3.05-m.) cubic elements weighing 25 tons, and cribbed for two or three

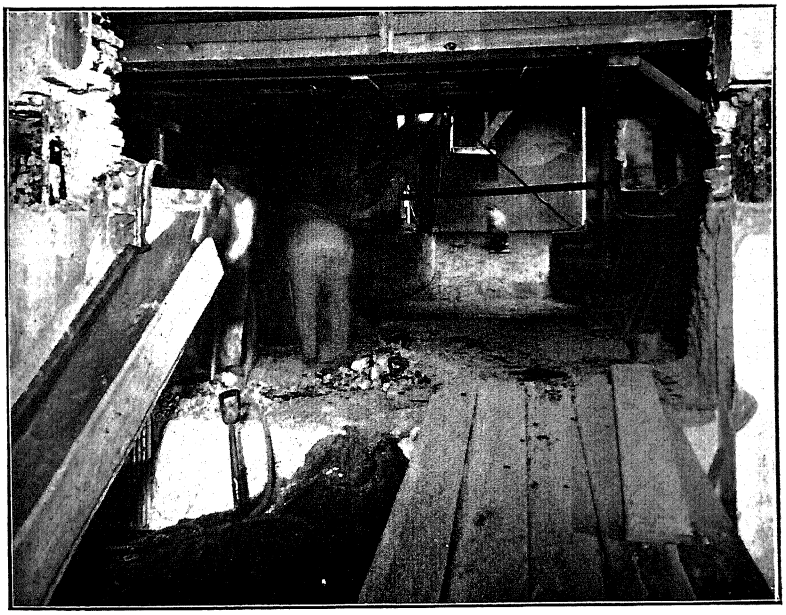
inches (50 to 75 mm.) clearance. The shaft walls are lightly supported, so all weight must be taken from lowest floor. Fig. 5 shows the section of a machinery entrance and passageway in another substation under construction, which had to be practically hewn out of a finished building basement. Fig. 6 shows a diagram of this same entrance.

Of really greater importance to these substations is the matter of air supply, because until recently all synchronous converters installed on the Chicago system had air-blast transformers and regulators and required under extreme conditions 10,000 cu. ft. (283 cu. m.) of air per minute per unit of 1000 kw. capacity. The temperature characteristic of these units is a 55 deg. cent. rise with an overload of 25 per cent and in many cases 50 per cent for two hours. With the temperature of the substation at 40 deg. cent. (104 deg. fahr.) and the street level temperature at 35 deg. cent. (95 deg. fahr.), it may be seen that the problem of bringing enough air to keep, say, six such units below maximum safe insulation temperature is no small one. Besides, the air must be taken away from the substation as fast as it is introduced, in order to avoid prohibitive back pressure.

Again, a comparison with a super-grade substation may be made to emphasize the dimensions of this problem. In the latter type, one usually finds a half basement construction with numerous windows, which serve the purpose of intakes, and an array of large windows, also perhaps a monitor in the superstructure, readily permitting the escape of the heated air,or perhaps 300 sq. ft. (28 sq. m.) of doorway which can be opened at will. Referring back to the picture of the concrete enclosed pit, built close to the lot lines, and bearing in mind the usual inviolability of building lines, one may imagine the difficulties in the way of adequate air supply.

The usual method of bringing in air is through a specially designed grating in the sidewalk, which must be so located that it will not inconvenience the public or the tenant whose business is carried on just above the substation. The street level location of the air intake gives rise to one of the most serious faults characteristic of air supply systems of this sort, viz., the unavoidable entrainment of large quantities of dirt. Grating, screens, and washing devices are of but little avail against the volumes of dirt swept along with the 40,000 or 50,000 cu. ft. (1130–1410 cu. m.) of air per minute which scours the street on its way to the intake.

[JAMIESON]
FIG. 4.—LOWERING TRANSFORMER INTO COURT PL. SUBSTATION



[JAMIESON]
FIG. 5.—MACHINERY INTAKE, SHERMAN STREET SUBSTATION

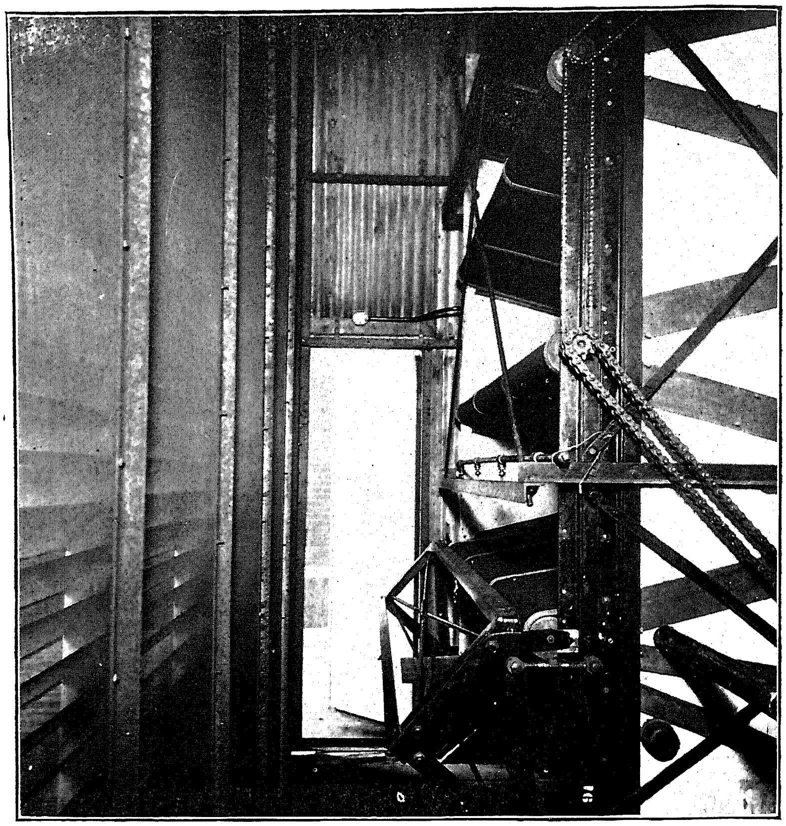


FIG. 7.—VACUUM-CLEANED AIR SCREEN, HARRISON STREET SUBSTATION [JAMIESON]

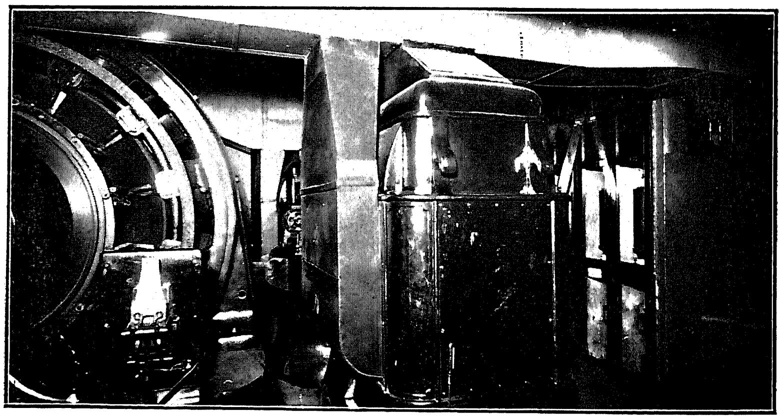


FIG. 8 [JAMIESON]

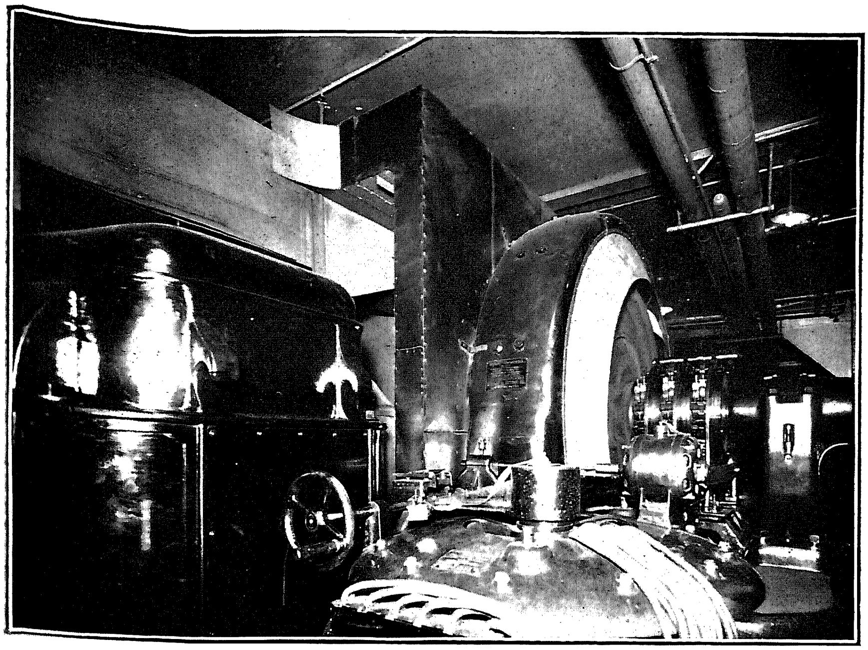


FIG. 9 [JAMIESON]

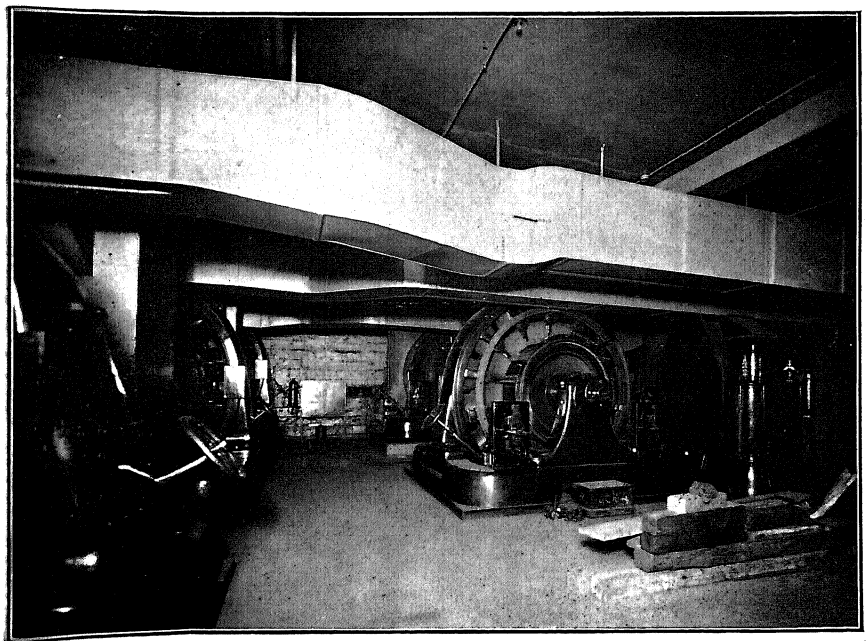


FIG. 10 [JAMIESON]

Again, during freezing weather, ice and snow make trouble and in some cases require special construction for their control. The dirt is, however, the most serious drawback. It can be removed from the exterior of accessible surfaces more or less easily, but when blown into the air ducts of an internally cooled transformer or regulator for a period of years, the weekly cleaning of apparatus retards but slightly the inevitable clogging of these passages. Manufacturers have been slow to recognize these conditions as unavoidable, but lately have offered some aid by the provision of internal ducts of less tortuousness, which may be more effectively cleaned.

The principal objections to air-cleaning chambers and devices have been first cost, space required, resistance to passage of air and operating expense. One promising new device is a screen, differing from ordinary screens, in that it is self-cleaning. That is, a motor-driven endless cloth screen travels past a fixed vacuum sweeper, and all dirt deposited can be removed as fast as desired by simply varying the rate of travel of the screen. This screen under test caused a surprisingly low drop of pressure, considering the thickness of cloth. Fig. 7 shows a partial view of this machine, viewed from the substation side.

Cooling air is drawn through the screening device, usually by blowers in duplicate and of the curved vane type, each usually having a capacity of 25,000 cu. ft. (708 cu. m.) per minute at $1\frac{1}{4}$ oz. (35.5 g.) pressure, and impelled through sub-floor ducts to the converting unit.

As constructed, air-blast synchronous converter outfits are not entirely adapted for service in these sub-grade substations. In the super-grade substations where multitudinous windows and large doors are possible, little attention is necessary to the disposal of the heated air, as the numerous exits tend to diffuse the air currents. In the sub-grade type, however, the direction that all air currents take upon leaving the room is generally towards a given point and this fact makes the cooling of adjacent converters very difficult. A synchronous converter is usually constructed as though it were intended to operate where cool air can impinge from all directions. When operating in an enclosed substation in close proximity to adjacent units where blasts of heated air are being thrown out by the complex fan action of their revolving armatures and drawn toward one corner of the room by the exhaust fan, they are subject to dangerous overheating. The transformers and regulators do not suffer

as much, proportionately, because of the structurally directed internal air blast. The obvious remedy is to treat the exhaust air as we treat the supply air, and lead it away through ducts, which is fairly easy in the case of the transformer. But to do this effectively with the synchronous converter is much more difficult. Radial, shaftwise, and eddy currents are so indiscriminate that the problem of corralling them and leading them off in ducts is very difficult without sacrificing accessibility of the working parts of the converter.

Figs. 8, 9 and 10 show some installations of this sort of exhaust duct system, which actually lowered the temperature of a 5000-kw. substation 11 deg. cent. (20 deg. fahr.).

The exhaust fan is usually a single unit of the positive blower type, in some cases of a capacity of 25,000 cu. ft. (708 cu. m.) per minute at $1\frac{1}{2}$ oz. (42.5 g.). Disk fans are inadequate, because of the resistance of available exhaust passages.

After the air has performed its cooling functions it must be disposed of at its intake rate of perhaps 60,000 cu. ft. (1700 cu. m.) per minute. It cannot be returned through the sidewalk, for such a blast would be a public nuisance, so advantage is taken of every available uptake towards the roof—the building stack or its shaft, any available ventilating or conduit shaft, or perhaps a separate duct, erected against the exterior wall in the light court.

For the service from battery rooms the exhaust blower and shaft must be impervious to acid fumes, which means special construction in each case. Bronze fans or lead-lined stacks were the standards of earlier practise, but owing to cost and difficulty with lead linings in stacks of considerable height, experience is being sought with plastered ducts. In one case a steel impeller with acid-proof paint seems to have met the requirements amply.

The difficulties experienced with the air-blast type synchronous converter outfits finally forced attention towards water-cooled units, the expense of water supply having long delayed consideration of this type. Three substations are in course of erection in Chicago which will utilize converter outfits cooled by water from the city mains. These units are of 2000 and 3500 kw. capacity. Air will still be required for revolving apparatus, but with the increase in capacity and the consequent reduction in number of units per substation, the problem of adequate housing and duct work to facilitate cooling is simplified.

The city water has an average yearly temperature of 10 deg.

cent. (51 deg. fahr.) and a summer temperature of 22 deg. cent. (72 deg. fahr.), which is much lower than available cooling air previously referred to. As the 3850-kv-a. transformer requires 24 gal. (90.8 l.) of water per minute at full load with a load factor of 32 per cent, the theoretical substation requirements average 2900 gal. (10,980 l.) per 1000 kw. per 24 hours. The calculation assumes the operation of units in a group of substations in exact conformity with the load curve in the district. The actual consumption will, of course, be in excess of this amount because of the manifest impossibility of accomplishing this without underloads. But since the periods of full load occur during the winter and we are dealing with absolute temperatures, overloads may be taken with less than proportionate increase in the gallons per minute consumption.

The theoretical temperature rise of this discharge water from a 3850-kv-a. transformer at full load is approximately 10 deg. cent. (18 deg. fahr.), which checks fairly well with results gained from operation of similar apparatus. This warm water, it is intended, will be wholly or partly sold to the building management, whose requirements may reach 50,000 gal. (189,270 l.) per day.

As the substations are developed and the amount of waste water attains economical significance some reclaiming or recirculating system will undoubtedly be adopted, but operating experience will afford the best guide to a selection of the proper system.

Fig. 11 shows the connections of the water and oil piping system. Attention is called to the fact that this is an open system, the street main pressure being depended upon to force water through the cooling coils and the discharge being open to atmosphere. All apparatus is, however, below the level of the street mains and sewer. Ejector pumps in duplicate are used to lift the water to the sewer from the discharge tank or to the building mains. Duplicate supply services from mains to different streets, duplicate ejector pumps and the general reliability of the water supply of a large city, all make for the security which must be a feature in a system of this kind.

In each of the 3850-kv-a. transformers there are 3100 gal. (11,730 l.) of oil which must be capable of being easily introduced, renovated, and replaced. The transformers are enclosed by compartments of concrete with doors of iron, which are practically tight. An open drain of 324 sq. in. (2090 sq. cm.) runs

beneath the several compartments and is intended to convey to a 3500-gal. (13,250-l.) pump, any oil which might be suddenly liberated from the transformer casing. A considerable piping system is needed for accomplishing this. Preliminary to the design of the oil piping system opinions were asked of engineers and manufacturers, regarding the necessity of providing for quick discharge of the oil in emergencies. Operating engineers favored this provision, but the manufacturers claimed that it is sufficient to close the transformer tightly in case of fire in order to retain the oil, and smother any flames which might occur.

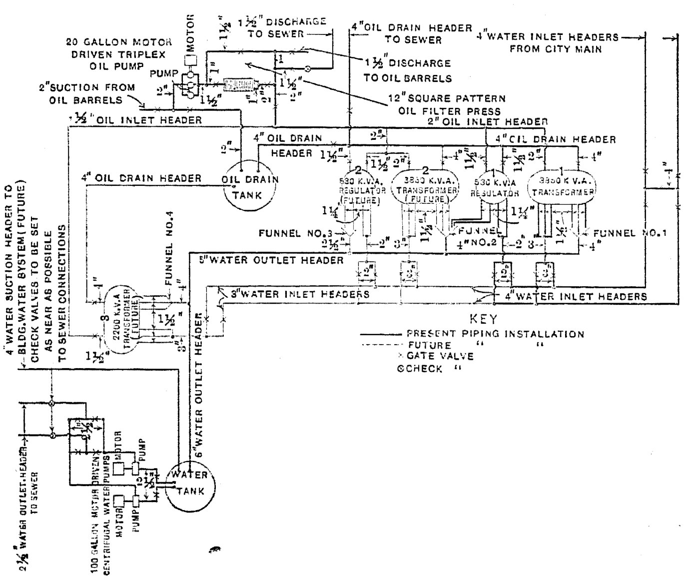


FIG. 11—DIAGRAM OF CONNECTIONS FOR OIL AND WATER PIPING FOR TRANSFORMERS AND REGULATORS

It is, of course, desirable to retain the oil in case of fire as this would undoubtedly lessen the damage to the transformer, but the oil may be liberated by an arc burning a hole through the case, in which event it may be very valuable to have means for quickly drawing off the oil.

In the diagram, Fig. 11, are several special features designed to increase the universality of the oil pipe system as much as possible, and the construction is such as to amplify in every possible way all precautionary features. The pumps, which are shown as a part of the oil filter system, are so connected that they

may serve either as filter or ejector pumps. Also the large sump shown, which is beneath the floor, may act either as a temporary storage of renovated oil or as a receiver for oil lost from a unit in service.

The reason for the apparently high structural cost of these sub-grade substations is the dual relation of the construction to the building itself and to the apparatus installed. It is expensive to construct deep walls actually proof against water leaking and to provide for locating machinery upon a floor, which serves also the purpose of holding the building together, because essential features of such a type of floor construction will generally limit its adaptation to other purposes. For instance, just at the point where cable space is needed behind a switchboard a false wall may require an extra foot (30 cm.), or just at the point where air ducts may be desired in the floor, a 36-in. (91-cm.) steel girder or its concrete equivalent may be located; or, as in one recent site, the whole floor must be reinforced so as to keep the earth below the building from being thrust upwards.

In one of the older substations where spread footing of columns claimed nearly 50 per cent of the available loading area of the basement floor, about one-half the weight of the battery, or 400 tons, had as a consequence to be carried on cantilever beams under the floor.

If the building in which the substation is to be located is an old one and only small units are to be installed, then the cost of the building construction required may be fairly low per unit but the cost per kilowatt high. If the building is an old one and the apparatus to be installed is of a size of the more modern units, then the cost of building construction per unit may be doubled, but the cost per kilowatt will be lower. If the building be a new structure and plans for substations can be made a part of building plans proper, the substation structural cost will be reduced very materially.

Building ordinances and other municipal regulations and interests play a considerable part in the development of these sites, and, together with the extraordinary nature of the business of the substation as compared with that of the average tenant of large down-town buildings, bring about some anomalous conditions. Ventilation, sidewalk restrictions, emergency exits, street and alley compensation and other matters not so prominent in ordinary construction, feature strongly.

It seems quite pertinent to emphasize a fact that has a bearing

on appraisals of this portion of an operating company's invested capital in rented properties. There is probably no portion of the company's real property where large sums of money may be invested for structural purposes with so little visible result as in the construction of a system of these substations. Conduit systems are more invisible, but a simple street chart and a few unit costs afford a very accurate guide to estimating of values.

The type of apparatus installed in these substations fixes the interior construction to a great extent. Synchronous converters are here practically the only type of units in use. Gross floor spaces of 0.95 sq. ft. (0.088 sq. m.) per kw. were average figures

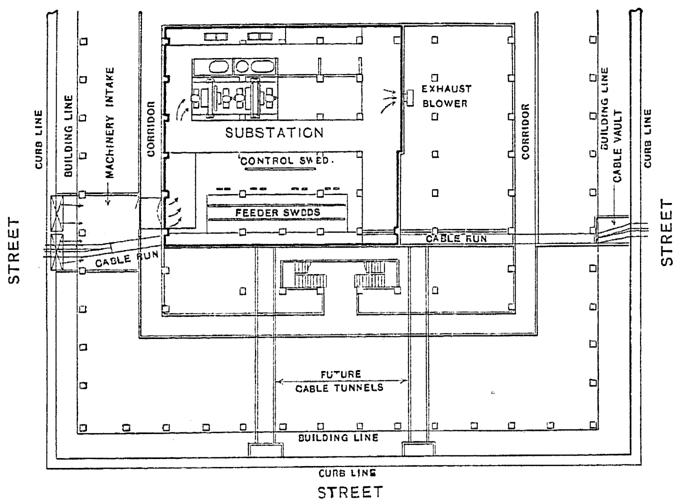


FIG. 12

for substations containing units up to 500 kw. capacity, whereas 0.54 sq. ft. (0.05 sq. m.) per kw. suffices for substations containing 3500-kw. units. Remembering that the transmission and distribution apparatus do not require any less space per kilowatt than they did with smaller units, it is clear that the large units have contributed wonderfully towards economy of space.

Figs. 12 and 13 show a plan and elevation of one of the largest and most modern substations of the sub-grade type which is under construction. This substation has 26 ft. (7.9 m.) head room, and floor space, including gallery, of 10,600 sq. ft. (985 sq. m.), which will permit of 16,000 kw. in converter capacity and a battery capacity of 1875 kw. (one-hour rate). One con-

spicuous feature is the ease of access to the conduit system in the three adjoining streets, a feature so seldom secured. The machinery intake is on a wide street where the volume of traffic is comparatively small, which is favorable both for machinery handling and air supply. Boilers in an adjoining room will assist in the disposal of heated air from the substation by their combustion requirements and may also help to dispose of the cooling water.

Favorable conditions such as these are not to be had with all

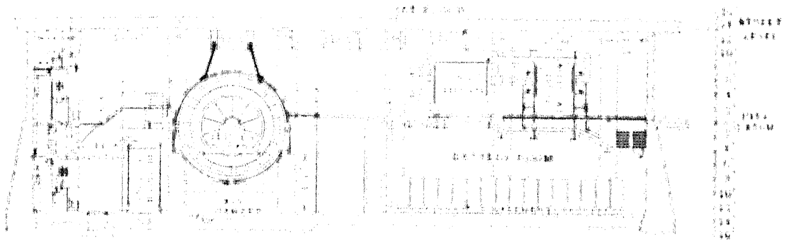


FIG. 13—SECTIONAL ELEVATION OF SUBSTATION SHOWN IN FIG. 12

sites secured, since many factors other than electrical or physical determine availability of locations, but withal the number and size of these prospective substations are rapidly increasing.

Because of the desire to treat these substations as a type, individual descriptions have been omitted and the characteristics of the type emphasized. For, with the increasing values of real estate in other large cities it is probable that this type of substation will awaken in the future a greater interest among electrical engineers.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 26, 1913.

OPERATION OF FREQUENCY CHANGERS

BY N. E. FUNK

The object of this paper is to discuss the general conditions governing parallel operation, the theory, practical operation, and methods of synchronizing two or more frequency changers consisting of two synchronous machines which tie together two systems of different frequency at one or more points. When only one frequency changer is used to connect two systems, all of the difficulties experienced in the parallel operation of frequency changers disappears, as the operation then involves only connecting a synchronous motor to one system and a synchronous generator to the other. The only difficulty in this case is the adjustment of the frequencies of the two systems to permit synchronizing.

Before any definite idea of the method of performing an operation can be grasped, it is necessary to understand fully the underlying principles governing the phenomena in question. These principles must be reduced to their simplest value, which, while affecting the accuracy of the final result, still presents it in the most comprehensive manner.

General Conditions

1. Suppose the motors and generators of two frequency-changer sets are in synchronism, and the motors only are connected to the bus. Since these motors are synchronous machines, they will keep both units of each machine in phase. The generator of one set is now connected to the bus and slowly loaded, while the other generator is allowed to run light. If the synchroscope is connected to these generators before any load is on the bus, the indicator will assume a position showing synchronism.

As the load is increased, the synchroscope indicator will slowly move away from the position of synchronism, the angle of variation being roughly proportional to the load. This voltage lag angle is due to the magnetic lag of the armature and mechanical lag of the fields of the loaded machine due to load. If it is necessary to parallel the unloaded machine with the loaded machine, this machine switch must be closed with the synchroscope needle out of synchronism, since it will assume the same lag as the loaded machine when it carries its share of the load.

2. If one of the sets is running unloaded, and the other set is brought from rest to full speed, preparatory to synchronizing, it will be noted after both synchroscopes have been connected that when one synchroscope indicates synchronism, the other one may be at various different positions on the synchroscope face, and vice versa. If the systems are 60-cycle and 25-cycle respectively, there will be twelve different indications of the 25-cycle pointer for synchronous indications on the 60-cycle synchroscope, and five different indications of the 60-cycle pointer for synchronous indications on the 25-cycle synchroscope.

Theory

1. Any alternating-current apparatus containing a current-carrying winding through which magnetic lines are passing, is subject to induced voltage drops. The armature of an alternator is no exception to this general rule. The voltage at the terminals of an alternator carrying load is therefore less than the generated voltage, by the vector difference of the generated voltage and the resistance and inductance drop. Fig. 1 represents a single-phase generator and is self-explanatory, inasmuch as it is the conventional clock diagram showing the voltage drop in a circuit containing inductance and resistance. In Fig. 1 let E equal the maximum value of the terminal voltage, E_g the maximum value of the generated voltage, and I the maximum value of the load current.

ωL inductive ohms of armature. R resistance of armature. $\cos \theta$ power factor of load current. To make the problem as simple as possible, consider unity power factor. This corresponds to actual conditions, as frequency changers are operated at 100 per cent power factor wherever possible.

Fig. 2 shows the voltage relations in this system. The voltage E lags behind the generated E_g by an angle that is roughly proportional to the inductance of the armature times the load

carried; since the inductance is fairly constant this angle may be assumed to vary with the load. The effect of resistance in Fig. 2 is to reduce the terminal voltage but not to make any great change in the voltage lag angle. The resistance effect will therefore be neglected in the following discussion. If the generator is assumed to be operating as a synchronous motor, the effect will be the same as in Fig. 2 except that E and E_g will now change places since the counter e.m.f. of the motor is less than the bus voltage by the drop in the motor armature. Assume that the frequency-changer set consists of a 60-cycle motor driving a 25-cycle generator. Let K_1 equal the proportionality factor by which the load L may be multiplied to obtain the lag angle of the bus voltage behind the generator voltage, and K, the same factor for the motor. α_1^0 and α^0 are the corresponding lag angles. Assume the set is carrying a given load L. The counter e.m.f.

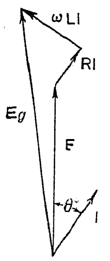


FIG. 1

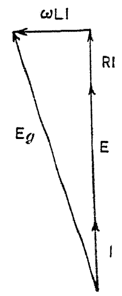


FIG. 2

of the 60-cycle motor will be α^0 behind the position it would assume at this instant if the motor were unloaded. $\alpha^0 = K\,L$. The field poles will be behind the position they would occupy at this instant if the machine were unloaded by $\alpha^0/p/2$ mechanical degrees, where p is the number of poles on the machine. The field poles of the 25-cycle machine are rigidly connected to the 60-cycle machine poles and are therefore the same mechanical degrees behind the position they would assume at this instant if the machine were unloaded. The maximum value of the 25-cycle generated voltage will occur

$$\frac{\alpha^0}{p/2} \times \frac{P_1}{2}$$

electrical degrees after it would occur if the machine were unloaded, p_1 being the poles on the 25-cycle machine. The bus voltage of the 25-cycle generator as in any generator will lag

behind the generated voltage by an angle proportional to the load. $\alpha_1{}^0 = K_1 L$. The maximum voltage of the 25-cycle bus will occur at an instant later than it would occur if the machine were unloaded by a time angle of

$$\alpha^0 \times \frac{P_1}{P} + \alpha_1{}^0 = L K \frac{P_1}{P} + L K_1 = L\left(K \frac{P_1}{P} + K_1\right) = \beta^0$$

and this lag angle will vary with the load. It should be understood that while the above relation is true only for unity power factor, it is a rough indication of what is happening in the armature of the set and is much more apparent than the complicated formula that illustrate actual conditions, which are given at the end of the article.

Having now established the fact that there is a time lag angle between the maximum values of the generated voltage when the machine is carrying load and when unloaded, the next step is to determine what effect this phenomenon will have in paralleling two frequency changer sets. If both sets were unloaded, it would only be necessary to parallel the machines when both 60-and 25-cycle synchroscopes indicate synchronism. Conditions change however, when it becomes necessary to parallel an unloaded set with a loaded set. The generator of the unloaded set will have no lag while the 25-cycle bus voltage of the loaded machine will have a time angle lag of

$$L\left(K \frac{P_1}{P} + K_1\right) = \beta^0$$

behind the position it would occupy if unloaded at this instant.

If the maximum voltage of the loaded machine is β^0 behind the position it would occupy if unloaded, and the maximum voltage of the unloaded machine coincides with the unloaded position of the loaded machine, then the unloaded machine must be ahead of the loaded machine by an angle β^0. It is necessary to close the 25-cycle switch of the unloaded machine when it is β^0 ahead of bus voltage in phase if it is to assume its share of the load.

If the 25-cycle machine were synchronized first, the indication of the 60-cycle synchroscope would show the motor voltage behind the 60-cycle bus voltage by an angle

$$\left(K_1 \frac{P}{P_1} + K\right) L = \beta^0{}_1$$

This can be easily understood after a moment's thought. For, since the loaded 25-cycle bus voltage is behind the position it assumes at this instant if unloaded and the 25-cycle unloaded machine is in synchronism with it, but has no time to lag in its own armature or the armature of the 60-cycle machine connected to it, the time lag of the loaded machine is reflected in the 60-cycle synchroscope indication of the unloaded machine.

The synchroscope indications will be as shown in the diagrams, Figs. 3, 4, 5 and 6.

LOAD TRANSFERRED FROM 60-CYCLE TO 25-CYCLE BUS

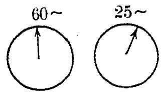


FIG. 3—60-CYCLE MACHINE SYNCHRONIZED FIRST

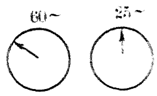


FIG. 4—25-CYCLE MACHINE SYNCHRONIZED FIRST

LOAD TRANSFERRED FROM 25-CYCLE TO 60-CYCLE BUS

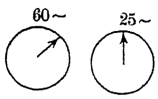


FIG. 5—25-CYCLE MACHINE SYNCHRONIZED FIRST

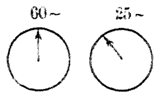


FIG. 6—60-CYCLE MACHINE SYNCHRONIZED FIRST

These four indications are the only indications obtainable when it is correct to put both ends of the set in parallel. Of course, the angles indicated on the synchroscope will vary from zero at no load on the running machine to an angle depending upon the value of the inductance of the armatures of the 60- and 25-cycle machines of the set and the load carried.

VARIATIONS IN SYNCHROSCOPE INDICATIONS

If above phenomena were the only troubles incident to paralleling frequency-changing sets in which the frequency of one machine is not a multiple of the other, there would be nothing more to say about the matter, but as a matter of fact, the most annoying part of the operation, to the operator at least, is the fact that there is only one set of poles on the unit at which synchronism occurs at the same instant on both the 60- and 25-cycle synchroscopes. That is, only one indication in twelve on the 60-cycle and one in five on the 25-cycle is the correct one for paralleling.

Consider a 24-pole, 60-cycle machine connected to a 10-pole,

25-cycle machine. Assume that a positive machine pole has come to rest under the middle of one of the phase windings in each machine. This position will indicate synchronism on both synchroscopes. Now, turn the fields until the second 60-cycle positive pole assumes the position that the first pole assumed. The fields will have been turned through

$$\frac{360}{12} = 30$$

mechanical degrees. The 25-cycle machine poles will also have moved 30 mechanical degrees but since the positive poles are

$$\frac{360}{5} = 72$$

mechanical degrees apart, the positive pole will not be near the middle of the winding and therefore will indicate some other than synchronous position on the synchroscope. The following diagram (Fig. 7) indicates the relation these various pole positions bear to one another.

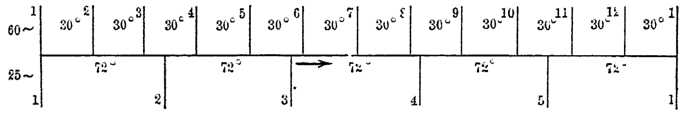


FIG. 7

The vertical lines above the horizontal line represent the middle of the positive poles on the 60-cycle machine and the vertical lines below the horizontal line represent the middle of the positive poles on the 25-cycle machine. Point 1 is the reference point and represents the middle point of an armature winding on one phase of each machine. The arrow indicates the direction in which the machines are supposed to be rotating. If the machines are revolving at the same speed and No. 1 point of both machines coincide, then both synchroscopes would indicate zero, but if No. 1 point of the 60-cycle No. 1 machine coincided with Point No. 6 60-cycle of No. 2 machine, then the nearest pole to No. 1, 25-cycle of No. 1 machine would be No. 3 pole of No. 2 machine which is $5 \times 30 - 2 \times 72 = 6$ mechanical degrees behind synchronous indication. If No. 2 machine is speeded up slightly then the 60-cycle needle will revolve five times before both No. 1 poles coincide, and the 25-cycle needle will revolve twice.

It is easily seen that at no point will be maximum value of the 25-cycle voltage occur simultaneously with the maximum value of the 60-cycle voltage except at zero or 360 which are one and the same point. To plot these indications on the face of the synchroscope it is necessary to construct a table showing the mechanical and then the electrical degree variations; considering first, synchronous indications on the 60-cycle synchroscope and then on the 25-cycle synchroscope. *O*, will be used to indicate synchronism, + or − indicates that the angle in question is clockwise or counter-clockwise from synchronous position. The tables are given below and in connection with the diagram will be readily understood when the first two steps are explained. Consider pole No. 1, 60-cycle. When this pole is under the middle of one phase of the armature winding the synchroscope indicates zero, the 25-cycle synchroscope will also show *O*, since No. 1 pole is supposed to be under the middle of one phase of the 25-cycle armature winding. Suppose that instead of No. 1 pole 60-cycle, No. 2 pole, 60-cycle was under the middle of the same phase winding. No. 1 pole, 25-cycle would then be 30 mechanical degrees behind the middle of the phase winding of the 25-cycle armature and be approaching it, therefore, it would be behind in phase relation or on the *slow* side of the synchroscope. Similarly No. 3 pole, 60-cycle would be at its maximum position when No. 2 pole, 25-cycle had passed the middle position of the reference line on the armature and therefore would indicate a leading phase position on the synchroscope; *i.e.*, the pointer, would be on the *fast* side of the synchroscope. The indications on the 60-cycle synchroscope are worked out in the same manner. (See Table II and Fig. 7).

The application of the data at hand is the next point to which to turn our attention. Suppose the set is being synchronized and the speed is slightly above synchronism. When the 60-cycle synchroscope shows synchronism, the 25-cycle is 90 deg. on the left hand side of the synchroscope face. Look in the table, and opposite −90 is found pole No. 4 on the 60-cycle machine. Since the machine is running fast this means that by the third time the 60-cycle pointer moves around the dial, the 25-cycle pointer will have reached synchronous position. If the machine were running slow, it would be necessary for the 60-cycle pointer to revolve 9 times before both synchroscopes showed synchronism. Instead of using the tables, it is much more convenient to construct a small indicator similar to a

synchroscope face and locate the values on this. As these markings will vary with the method of synchronizing, as will be explained later, the general methods of starting will be taken up and the use of the calculator illustrated for each case.

TABLE I

Pole No.	Syn. indications 60 ~	Syn. indications 25 ~ mech.	Syn. indications 25 ~ elec.	Pole No.	Syn. indications 60 ~	Syn. indications 25 ~ mech.	Syn. indications 25 ~ elec.
1	0	0	0	7	0	−36	−180
2	0	−30	−150	8	0	+ 6	+ 30
3	0	+12	+ 60	9	0	−24	−120
4	0	−18	− 90	10	0	+18	+ 90
5	0	+24	+120	11	0	−12	− 60
6	0	− 6	− 30	12	0	+30	+150

TABLE II

Pole No.	Syn. indications 25 ~	Syn. indications 60 ~ mech.	Syn. indications 60 ~ elec.
1	0	0	0
2	0	−12	−144
3	0	+ 6	+ 72
4	0	− 6	− 72
5	0	+12	+144

Methods of Starting

1. By induction motor or d-c. motor mounted on shaft of frequency changer set.

2. By using one of the machines of the frequency set as an induction motor.

First Method—Induction Starting Motor. This motor is usually of the wound rotor type. Suppose load is being transferred from the 60-cycle to the 25-cycle bus. The process of starting is as follows. The induction motor is put on the bus with all the resistances in the rotor, and as the machine comes slowly up to speed this resistance is cut out. The fields of both synchronous machines are put on and the 60-cycle field is adjusted to give 60-cycle bus voltage. It is impossible so to adjust the rotor resistance that exact synchronizing speed is obtained, since changes in resistance due to heating will change

the slip and the steps in the resistance would have to be very large in number with small values between the steps. Proper speed may be obtained by using the resistance step that gives the nearest value to synchronous speed and obtaining the finer adjustment by varying the 25-cycle field. This changes the iron loss in the 25-cycle armature and thus the load and slip on the induction starting motor. The 60-cycle machine will be synchronized first and then the 25-cycle machine will be put on, as it is more logical to connect the motor to the source of supply before connecting the generator to the load. It is now necessary to construct our synchronizing indicators before we can intelligently synchronize our machines.

These synchronizing indicators consist of small cardboard representations of the synchroscope face with a revolving disk attached. On this disk are shown the synchroscope pointer and the positions the pointer will assume at other than synchronous indications. In Fig. 8 the outer circle represents the stationary disk of the indicator while the inner circle is the revolving disk.

The outside circle, Fig. 8, is divided into 36 10-deg. spacings and these same divisions are marked on the 25-cycle synchroscope face. The inner movable disk is divided into 12 divisions corresponding to each position that the 25-cycle pointer assumes when the 60-cycle pointer indicates synchronism. The 10-deg. spacings are numbered arbitrarily and no numbers are used higher than 9 to save confusion when standing at a distance from the synchroscope. The 12 spaces on the moving disk are laid off as follows. (See Table I and Fig. 7).

When both 25-cycle and 60-cycle machines are in synchronism, the indication is as shown by the black synchroscope dial hand. When 60-cycle pole No. 2 is at No. 1 pole position, the 25-cycle pointer will have to move 150 degrees while the 60-cycle pointer moves around the dial once if the machine is running slightly above synchronism; therefore, the position marked 1 on the 25-cycle synchroscope means that the 60-cycle synchroscope pointer must make one more complete revolution before both will be in synchronism. If the machine were running slightly below synchronism, the correct pole for synchronizing would be moving farther away from the synchronizing position and it would be necessary for the machine to make a complete revolution relative to the running machine; therefore, the 60-cycle synchroscope pointer would be compelled to revolve 11 times before both pointers would indicate synchronism simultaneously.

In a similar manner, when No. 3 pole, 60-cycle is at No. 1 pole position, No. 2 pole 25-cycle is 60 degrees ahead in phase, and it is necessary for the 60-cycle synchroscope pointer to revolve 2 times fast, or 10 times slow before both are in synchronism. The 60-degree mark is therefore labelled 2 fast or 10 slow. The small arrows indicate the direction in which the needle is rotating. In this manner, all the other points are labelled.

In the first part of this paper, the lag angle due to load was explained. On the top of the stationary dial to the right and left are laid off the markings indicating the position of the pointer for various loads. The method of obtaining these load markings is given at the end of this paper.

To continue with synchronizing the machines. Suppose the amount of load carried by the running machines is X (See Figs. 8 and 3). Both synchroscopes are revolving slowly in the fast direction. Set the pointer to X, this revolves all the indications for other than synchronous positions as it should, since they are affected by load as well as the synchronous position of the pointer. Suppose the 25-cycle pointer lies between 8 and 9 (y) when the 60-cycle pointer shows synchronism (by inspection it will be seen that is the point 10⟵⟶2 will assume when the inner dial is shifted). This means that the second time the 60-cycle pointer rotates around the dial face and comes to synchronism is the proper time to close the 60-cycle switch. When this has occurred the 25-cycle pointer will occupy the position indicated by X. The 25-cycle field is then adjusted and after the starting motor has been taken off, the 25-cycle switch is closed, with the 25-cycle pointer about 22 deg. ahead of the bus in phase. The machine will assume its correct share of the load.

If instead of rotating fast, the synchroscopes had been rotating slowly, then the 60-cycle pointer would have rotated 10 times before the 25-cycle pointer would have reached X when the 60-cycle pointer indicated synchronism.

If the load was being transferred from the 25-cycle bus to the 60-cycle bus and the machines were synchronized in the same sequence as before, the point marked X_1 would be the proper indication of the 25-cycle pointer when the 60-cycle switch should be closed (see Figs. 6 and 8). The last method should only be used when there is some reason for not using the 25-cycle switch for synchronizing purposes.

Suppose that all the conditions of starting are the same as stated for the above, except that load is to be transferred from

the 25-cycle to the 60-cycle bus and that the 25-cycle machine, being the motor, is to be synchronized first. A new synchronizing indicator is necessary, and will show on the 60-cycle synchroscope the number of times that the 25-cycle pointer must revolve before the 25- and 60-cycle synchroscopes will indicate synchronism simultaneously. This indicator is constructed the same as Fig. 8, except that Table II and Fig. 7 are used. The load lag angle will be greater on the 60-cycle synchroscope than on the 25-cycle. Suppose for a given load the electrical degrees displacement are 10 in both armatures, the lag on the 25-cycle synchroscope is

$$10 \times \frac{5}{12} + 10 = 14.16 \text{ deg.}$$

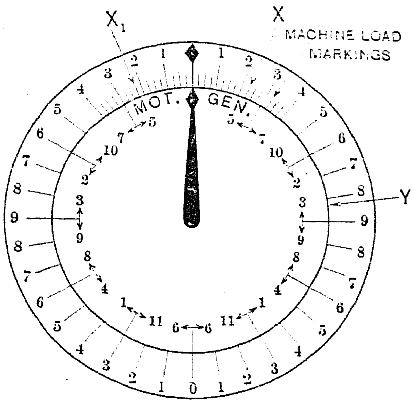


FIG. 8

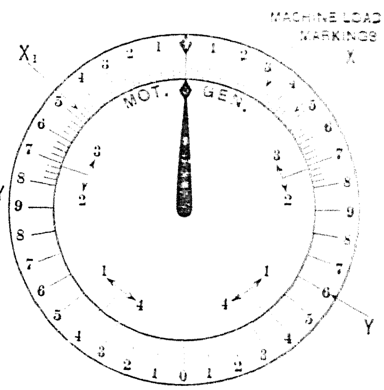


FIG. 9

and on the 60-cycle synchroscope is

$$10 \times \frac{12}{5} + 10 = 34 \text{ deg.}$$

The operation of synchronizing is the same as for Fig. 8, except 25-cycle is substituted where 60-cycle is used, and vice versa.

The only difference in operation where a d-c. starting motor is used is that it is possible to obtain correct synchronous speed by adjusting the d-c. motor field and it is therefore unnecessary to use the synchronous generator field as a speed adjusting medium.

Second Method. Assume the 60-cycle machine acting as a motor and load being transferred from the 60-cycle to the 25-

cycle bus. The 60-cycle machine is started at reduced voltage by an auto-starter or some other means. When the machine has reached full speed the field is put on both units. It is now necessary to construct a synchronism indicator since only one synchroscope will be available for synchronizing. The 25-cycle synchroscope will be laid off as before, the only difference being that the markings now indicate the number of times the 25-cycle pointer must pass synchronous indication before the proper synchronizing point is reached. This may be constructed from table I and Fig. 7, or from Fig. 8 by multiplying the numbers on the dial by 5/12 and discarding the remainder. The closing of the 60-cycle motor field locks the set in synchronism on the 60-cycle side. Suppose the 25-cycle pointer is at x, this cor-

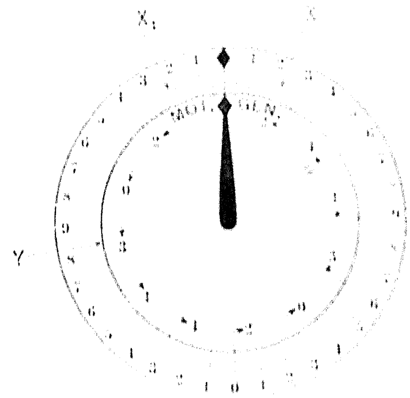


FIG. 10

FIG. 11

responds to 1 on the revolving dial when the pointer has been placed at X. The field of the 60-cycle motor is now taken off and the 25-cycle pointer will begin to revolve in the slow direction. When it has passed synchronous position once and reached the point 0, the 60-cycle field is again closed, which locks the motor in synchronism. The 25-cycle pointer will now stand at X.

The 60-cycle machine is thrown from starting to running voltage taps and the 25-cycle machine switch is closed. If all conditions were the same ,but the load were being transferred from the 25-cycle bus, the indicator pointer would be set at X_1, but all the operations ,would be the same, assuming the 60-cycle machine was the one equipped with the starting device. If the 25 cycle machine was equipped with the starting device, the operation would be the same as before, assuming that the load transferred

from 25-cycle to 60-cycle bus, 25-cycle inserted for 60-cycle and vice versa. The synchronism indicator shown in Fig. 11 would then be used, showing indications on the 60-cycle synchroscope of the number of times the 60-cycle needle must pass synchronous indication before the proper time for synchronizing. Fig. 11 is obtained from Fig. 9 by multiplying by 12/5 and dropping the remainder, or from Fig. 7 and Table II.

All instances in the above cases have depended on the assumption that there was the same percentage inductive drop in the armatures of both sets.

A difference in size can be accounted for on the indicator as follows. If the running machine is one half size, take twice the load it is carrying on the indicator, assuming that the indicator is calculated, for the largest machine, or the load indications may be left off the indicator and a table made showing the lag for each machine in terms of the 10 degrees spacing, (see Tables III and IV). These tables show No. 1 small, No. 2 next, and No. 3 the largest machine. The values were arbitrarily set down and do not indicate actual values.

TABLE III

25 ~

Load kw.	Machine No. 1	Machine No. 2	Machine No. 3
500	0.8	0.4	0.2
1,000	1.6	0.8	0.4
1,500	2.3	1.1	0.6
2,000	2.9	1.5	0.8

TABLE IV

60 ~

Load kw.	Machine No. 1	Machine No. 2	Machine No. 3
500	1.9	0.9	0.5
1,000	3.8	1.9	0.9
1,500	5.5	2.7	1.4
2,000	6.9	3.5	1.9

Effect of Different Percentages of Armature Inductance on Parallel Operation of Frequency Changers

If the machines have different percentages of inductive drop, then when all are in parallel, they will not share the load equally. This may be overcome by arranging one of the armatures of each

set so that it may be revolved, and by shifting the various armatures it is possible to make the machines share the loads equally at some one point, but in this event the machines will not share the load satisfactorily if load is transferred in the reverse direction. For example, consider the inductance of one machine such that the generator and motor voltages have a time lag of 10 mechanical degrees at full load over the no load value, the other machine 15 mechanical degrees. If these machines are in parallel, the lag angle must be the same in both, and if we consider the angle proportional to the load, No. 2 machine will only carry 66 per cent of full load when No. 1 is fully loaded. To enable the machines to divide the load evenly it would be necessary to shift No. 2 motor armature ahead, or No. 2 generator armature back, considering direction of field rotation as forward movement. If the direction of power transfer was now interchanged the machines would not share the loads as well as before

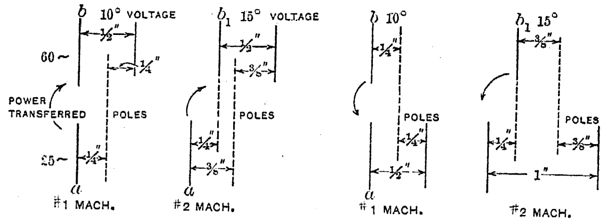


FIG. 12

the armatures were moved. Fig. 12, while not mathematically correct, shows clearly why this is so.

In this figure, a and b are the mid-points of the armature windings of the machine with a 10-degree lag angle represented by $\frac{1}{4}$ in., and a_1 and b_1 are the mid-points of the armature of the machine with a 15-degree lag angle represented by $\frac{3}{8}$ in. Suppose power is transferred from 25-cycle to 60-cycle bus. The lag in the 25-cycle armature is $\frac{1}{4}$ in. (this is the mid-point of the poles). The lag in the generator armature is $\frac{1}{4}$ in., thus making the amount the 60-cycle voltage lags $\frac{1}{2}$ in. In machine No. 2, the armature is moved ahead $\frac{1}{4}$ in. and the lag of the motor armature is $\frac{3}{8}$ in. (this is the mid-pole position). The generator armature lag is $\frac{3}{8}$ in. making a total of $\frac{1}{2}$ in., and since these two angles are the same, the machines will each take their share of the load. If the direction of power transfer is reversed, No. 1 machine still shows a lag of $\frac{1}{2}$ in. but No. 2 is $\frac{3}{8}$ in. on the

motor end, $\frac{3}{8}$ in. on the generator end plus $\frac{1}{4}$ in. that the armature has been moved, making 1 in. or twice the lag of No. 1 machine, in consequence No. 1 will carry 140 per cent load and No. 2 will carry 60 per cent load, assuming machines to be of equal capacity and the total load equal to the combined capacity of both machines.

$$X = \text{No. 1 machine load}$$

$$Y = \text{No. 2} \quad \text{"} \quad \text{"}$$

$$\frac{X\frac{1}{2}}{100} = \frac{\frac{3}{4}Y}{100} + \frac{1}{4}$$

$$X + Y = 200$$

$$\frac{1}{2}\frac{(200 - Y)}{100} = \frac{\frac{3}{4}Y}{100} + \frac{1}{4} \times \frac{100}{100} = \frac{\frac{3}{4}Y + 25}{100}$$

$$100 - \frac{Y}{2} = \frac{3}{4}Y + 25$$

$$75 = \frac{5}{4}Y$$

$$Y = \frac{4}{5} \times 75 = 60$$

$$X = 200 - 60 = 140$$

This shows that great care must be taken in writing the specifications for purchasing frequency changers, that are to transfer load alternately from one frequency to another, and still greater care in designing them. For while it is possible to arrange the set so that the load will be properly divided at some specific point when transferring load in a given direction, no matter if the per cent inductance varies considerably, the sets will not operate satisfactorily when the direction of load transfer is reversed. This statement of course, applies only to the case where two sets are operating in parallel in the same station, as where two systems are tied together by two frequency changer sets located in different stations, the line inductance determines

to a great extent the proper division of the load. With only one set connecting two systems, however, the phase angle of the frequency changer set has nothing to do with the amount of load it carries. The amount of load being determined in this case by the governor settings of the prime movers of the respective systems.

Formulas for Phase Angle Variations of Frequency Changer Units

$\omega L I$ = Inductive voltage drop in motor armature, at load I
$r I$ = Resistance " " " " " " " "
I = Load current of motor.
E = Bus voltage, motor.
θ = Power factor angle, motor.
α = Lag angle, motor.
f = Motor frequency.
f' = Generator "
α' = Lag angle, generator.
θ' = Power factor angle, generator.
E' = Bus voltage, generator.
I' = Load current, "
$r' I'$ = Resistance voltage drop in generator armature at load I'.
$\omega' L' I'$ = Inductive voltage drop in generator armature at load I'.

$$\mathbf{L} = \frac{\omega L I}{E}$$

$$R = \frac{r I}{E}$$

$$\mathbf{L}' = \frac{\omega' L' I'}{E'}$$

$$R' = \frac{r' I'}{E'}$$

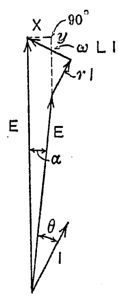


FIG. 13

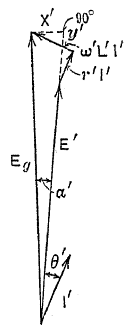


FIG. 14

α_t = the total phase angle of generator.

$$\cos \alpha = \frac{E - Y}{\sqrt{(E - Y)^2 + X^2}}$$

$$Y = r\,I\cos\theta + \omega\,L\,I\sin\theta$$
$$X = \omega\,L\,I\cos\theta - r\,I\sin\theta$$

$$\frac{r\,I}{E} = R$$

$$\frac{\omega\,L\,I}{E} = \mathbf{L}$$

Substituting,

$$\cos\alpha = \frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2\,(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$

$$\cos\alpha' = \frac{E' + Y'}{\sqrt{(E' + Y')^2 + X'^2}}$$

$$Y' = r'\,I'\cos\theta' + \omega'\,L'\,I'\sin\theta'$$
$$X' = \omega'\,L'\cos\theta' - r'\,I'\sin\theta'$$

$$\frac{\omega'\,L'\,I'}{E'} = \mathbf{L}'$$

$$\frac{r'\,I'}{E'} = R'$$

Substituting,

$$\cos\alpha' = \frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}}$$

$$\alpha_T = \alpha\,\frac{f'}{f} + \alpha'$$

$$\alpha = \cos^{-1}\frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2\,(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$

$$\alpha' = \cos^{-1}\frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}}$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$
$$+ \cos^{-1}\frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}} \qquad (1)$$

It is usual to operate frequency changer sets at unity power factor. Therefore

$$\cos\theta = \cos\theta' = 1$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1 - R}{\sqrt{1 - 2\,R + R^2 + \mathbf{L}^2}}$$

$$+ \cos^{-1}\frac{1 + R'}{\sqrt{1 + 2\,R' + R'^2 + \mathbf{L}'^2}} \qquad (2)$$

The resistance drop at unity power factor has its greatest effect in varying the voltage but only a small effect in varying the lag angle, let us therefore assume that the resistance is zero.

$$R = R' = 0$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1}{\sqrt{1 + \mathbf{L}^2}} + \cos^{-1}\frac{1}{\sqrt{1 + \mathbf{L}'^2}} \qquad (3)$$

Assuming that the angles are small, we can see from Fig. 15 that they are proportional to L and L' which are proportional to the loads as we assumed in the beginning of this article.

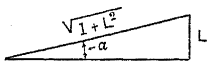


Fig. 15

$$\therefore\ \alpha_T \propto \text{load}$$

Method of Obtaining Load Readings

It is possible, if the constants of the machines are known, to obtain the markings on the synchronizing indicators by calculating from formula (1) or fairly accurate results may be obtained from (2) or (3), but the best and most practical way is to run one machine loaded and another one with only the motor connected. The generator synchroscope is then put on and the indications of the pointer are noted for various loads on the running machine. These readings may be plotted on the indicator or in a table as shown earlier in this paper. There are many more interesting points in the operation of frequency changers, but the object of this article was to deal only with the synchronizing of these machines.

DISCUSSION ON "AUTOMATIC SUBSTATIONS" (SUMMERHAYES), "CONVERTING SUBSTATIONS IN BASEMENTS AND SUB-BASEMENTS" (JAMIESON) AND "OPERATION OF FREQUENCY CHANGERS" (FUNK), COOPERSTOWN, NEW YORK, JUNE 26, 1913.

D. B. Rushmore: I will bring up certain points of unusual interest in the situation brought forward in Mr. Summerhayes's paper on automatic substations, because of the possible large development along this line. There is such a large field of application of electric energy, and such a large field of undeveloped sources of power now awaiting the man who can reduce the cost of operation, either of application or development, that it is an interesting subject to consider.

In a great many places there are operating conditions in which an automatic substation would allow electricity to be used where otherwise it would be uneconomical, and in the big field of agricultural operations, it would appear that there might be considerable use of such installations. There is already in existence a small substation in which the machinery is supposed to run indefinitely. Mr. Moody has put a continuous-running substation on a pole, without any attendance, and put a revolving machine there which is supposed to run indefinitely, almost without inspection. In mining work, especially, and in work subject to labor disturbances, the advantages of automatic substations are very evident, and it is very interesting to look forward and see the possible growth of this work.

F. D. Newbury: Mr. Summerhayes's paper is an interesting solution of a very difficult problem. I would like to hear, though, from some of the operating men, as to their feeling in connection with the operation of fairly large machines without superintendence at all times. There has been, of course, a large amount of remote-control machinery installed, but it has been, in general, in relatively small capacities and of course, in practically all cases the machinery has been of the non-commutating type. Remote control is certainly in the direction of economy, and it will undoubtedly continue to develop. It is, moreover, directly in line with the extensive use of outdoor transformer and oil switch substations, which two or three years ago were looked upon with a good deal of skepticism, if not disfavor.

There are two minor points in the paper I would like to refer to. The possibilities of the converter coming up with the wrong polarity is nicely taken care of in this case by separately exciting the converter. Separate excitation, however, will not be generally available. This is particularly true of railway substations that do not have a storage battery or other direct-current source of supply.

The two-thirds voltage switch also is mentioned, but I do not believe that that additional application is necessary—certainly not in the 500-kv-a. converter—and the switching could be

considerably simplified by using only one starting voltage instead of the two.

In Mr. Jamieson's paper, I wish to emphasize from the designer's standpoint the necessity for an adequate supply of cool, clean air. As Mr. Jamieson well points out, it is difficult to obtain, but it is absolutely necessary to the life of the machines if they are to be operated at a rate that is at all economical. With substation air temperatures of 40 deg. or 45 deg. very little is left between that and a permissible 90 deg. for temperature rise in the apparatus.

In connection with the cleaning of the air, Mr. Jamieson mentions an ingenious vacuum air filter. Several air washing outfits have been developed and have been used to a limited extent in this country and quite extensively abroad. That, I should think, would be particularly adapted to the restricted space of substations in basements, and I would like to know if it has been applied to that work.

In connection with Mr. Funk's paper, while it is somewhat outside the range of his paper, I would ask if he has had any experience with the use of pumps in order to introduce oil pressure under the bearings before starting, in order to facilitate starting. That has been considered, and I know such a system has been installed. If he has had any experience with such an outfit I would be glad to know the results.

F. C. Caldwell: In connection with the paper on automatic substations, I would call attention to the fact that an automatic resetting circuit-breaker is now being developed and will shortly be on the market. This breaker, of course, opens when there is an overload and then will not close again until the overload goes off of the direct-current circuit. As soon as this happens the breaker closes and is again ready for operation.

Paul M. Lincoln: I am reminded by Mr. Summerhayes' paper of the old saying that the proof of the pudding is in the eating, and not in the chewing of the strings of the pudding-bag. I consider that our getting up here and talking about this matter of distant operating substations is considerably in the nature of the chewing of the strings of the pudding-bag. The crux of the matter lies in how it operates, and whether it gives satisfaction to the operators, and whether it is cheap. We are told by Mr. Summerhayes it has been in operation for some time and gives promise of being a solution of the problem of substations operated without attendance. I trust so, and I believe that Mr. Summerhayes is to be congratulated on working out the details of the automatic substations so completely.

H. M. Hobart: As to Mr. Newbury's suggestion about washing the air, it may be interesting to mention that the London Electric Supply Station at Deptford has several large turbo-generators, of 5000 kw. each, which supply the London, Brighton & South Coast Railway with power, and the air is being washed by being passed through sprays of water. This is the largest

installation of this character, I believe. Water filters are also used for washing the air supplied to the turbo-generators of the Brighton Electricity Supply Corporation. The system performs the additional function of cooling the air, as well as washing it. If the air is cleaned by filtering it through cloth screens the screens gradually become clogged up, and the machines will get very hot, until the screens are cleaned, whereas by passing the air through water sprays nothing can get out of order.

Henry W. Peck: Mr. Summerhayes's paper was very interesting to me, as I have had some operating experiences along the lines dealt with in the paper.

Regarding Mr. Newbury's suggestion, I would have little hesitation in applying such a system in certain cases. In the stations the trouble comes so quickly that even if you have an operator you are relying on the automatic regulation to protect the station and the system. If the automatic equipment does not work, your main station, or the equipment of it, is apt to be seriously damaged even if you have attendants there.

I would like very much to have Mr. Summerhayes work out this idea along the line of our discussion yesterday regarding synchronous condensers. It might be somewhat more difficult than the station which he describes in his paper, but I am not sure that it would be. You would then obviate the difficulty suggested yesterday of having inefficient operators with whom to trust the operation of the synchronous condensers. Thinking it over very briefly, I can see no difficulty in arranging automatic devices to get the desired effect of field strengthening or weakening to vary with the conditions. It seems to be no more difficult than some things which our designing engineers have accomplished. The economy of such an automatic station is especially great in view of the feeling on the part of operating men that more than one man must be present in any building which contains high-tension or even moderate tension electrical apparatus. The presence of two men in the station is required in some states by law, or city ordinance. Many companies feel it is not safe, even though there is no law requiring it, to have less than two in the station. This means that even in a small station, where there is not enough to keep one man busy one-quarter of his time, we must have two men present at all times. The economy, therefore, of a station without attendants is exceedingly great.

S. D. Sprong (by letter): This paper presents a rather novel adaptation of standard apparatus as a commercial expedient. The plans as shown reveal a very careful working out of the elements of the problem and an excellent judgment in the selection of the automatic devices to meet the unusual condition of absence of manual operation and immediate supervision.

It is, however, this very complete provision for remote control and automatic means to prevent damage to the apparatus that emphasizes the point which the author seems to consider of

paramount importance. I refer to the fact that there is apparently no special thought or provision to safeguard the service even though at the possible expense of the equipment. Continuity of service, especially in an underground district of this character, should have first consideration under all conditions and it is a frequently emphasized rule among most light and power companies to maintain service even when it may probably result in damage to apparatus or equipment. The author appears to take quite the contrary view in that all the automatic and other provisions for meeting emergencies are designed to safeguard the apparatus, which exaggerates much beyond its true relative value the safety of the equipment as compared with the maintenance of service. I believe that any section of the city that would justify the installation of an underground d-c. system, is of such importance as to justify the relatively small additional expense of substation operators, the wages of which when capitalized would secure more of the elements that go to the maintenance of satisfactory service and the meeting of emergency conditions than any elaboration or duplication of automatic safety devices and methods of remote control.

I would suggest as an alternative, the employment of a substation operator covering a ten-hour period from 4 p.m. to 12 midnight, which would cover the heavy load period, and during the remaining fourteen hours and Sundays the lighter load could be carried by trunk feeders from one of the regular substations and controlled by pressure wires. Assuming the low load factor of 25 per cent this would give about 1,000,000 kw-hr. output per year. With a labor cost for the single operator of about $800 it would show about eight hundreths of a cent per kw-hr. additional cost on the whole consumption in this district. As the character of the load in this district is almost entirely retail and therefore at the maximum rate, an additional output cost of eight tenths of a cent would be more than offset by the numerous advantages to be obtained in such a district by having an operator in charge during important hours of the load.

H. R. Summerhayes: Mr. Newbury referred to the possibility of operating large machines without attendance. I think that large machines are possibly more reliable than small ones. It is only on account of the larger investment involved that people would hesitate to extend this principle to very large machines. Where the investment is so large that you can afford to have an operator on account of certain hazards, such as the fire hazard, for instance, the advantage of this form of automatic operation is not so great as in cases where the attendant is not required on account of the fire risk. So far as the operation of a machine is concerned, I should think the larger machine is fully as reliable as the smaller one.

In reference to the matter of polarity, also brought up by Mr. Newbury, Mr. J. B. Taylor devised several years ago a polarized relay to be connected across the commutator, across the brushes,

and as the machine goes up to synchronism, that relay would be getting alternating current. As it came very near synchronism, it would be polarized current, and the relay would be prevented by a dashpot, from going to its full travel. It would not operate finally, until synchronism had been obtained, when direct current would be supplied to it, and then it would operate in a direction determined by the polarization of the relay.

J. C. Lincoln: Suppose it happens to get in synchronism, so the relay was kept out, what is there to make the relay slip forward?

H. R. Summerhayes: It will be arranged to reverse the connections so that it is connected to the bus in the right direction.

Mr. Newbury brought up the point of the two-thirds voltage switch. When we first laid out this remote power plant, we started on one voltage, and threw on all the voltage, but it was thought desirable to put in an extra switch, because we were not sure at first exactly what field strength would have to be used, and as a matter of fact, we can go through from one-third voltage to full voltage without creating any disturbance, but in order to do so we must first make the full field, which can be done, but the field on this machine is so strong that there is somewhat more disturbance in throwing over with a strong field than by the method used.

Mr. Peck referred to the operation of synchronous condensers automatically, that is, automatically restarted, I suppose. I think a synchronous condenser can be arranged so as to be operated by an automatic voltage regulator, and operated practically without attention. Either that, or a synchronous motor can be arranged so that if the power goes off the transmission line, and then comes back again, the motor can be restarted. I know of a case now where it is planned to put in a restarter for a synchronous motor. In this case a town is lighted by a frequency changer, a 60-cycle line, the synchronous motor driving this set being supplied from a 25-cycle transmission line. The apparatus is modern and the operator does not spend much time in the station, but is able to give a large part of his time to other duties. Everything operates all right except when the power goes off the line, and then the frequency changer shuts down and the operator must go back and start up. I proposed an equipment for that station so arranged that when the motor falls out of step it will be thrown on the starting taps, so that when the power comes back it will be automatically restarted, and the proper arrangements for field and load will be taken care of automatically.

Mr. Lincoln asked if the operation is satisfactory. I do not know whether there are any of the Detroit Edison people here, but Mr. Cato intended to be here. I recently talked with Mr. Cato and he said he has not heard from the station for a long time, that they send a man there once a day to inspect it, and he has not heard any complaint regarding the station, and that it operates satisfactorily.

As to the heating of the building, this substation in Detroit is not heated, and that expense is saved as well as the expense of the operator.

D. W. Roper: The only question raised, I believe, was as to the cleaning of the air supply, suggesting that this be done by washing rather than by screening. In the substations covered by Mr. Jamieson's paper, the limitation, I believe, has been generally found to be one of space, for the washing scheme requires more space than the air screening system. The washing system has been tried in one or two of the smaller installations, and the reason for its lack of success was because there was not sufficient space for a proper installation. However, if a screen device with a vacuum cleaner can be worked out, it would appear to be simple and require less attention than the washing scheme.

N. E. Funk: Concerning the oil pressure supply to the bearings to make the machine start easily, in the case of the two machines I have in mind, one 3000 kw. and one 6000 kw., it was not necessary to use oil pressure in the bearings of the small machine, as it started easily. It was impossible to start the 6000-kw. machine with a 600-h.p. motor consuming about 1200 kv-a. unless an oil pressure of 150 lb. per sq. in. was applied for about 3 min., and then it started very slowly. If oil pressure was applied for about 5 min. a crack was heard in the bearings indicating that the shaft had lifted from the bottom of the bearing, and the machine started easily.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

THE ELECTRIC STRENGTH OF AIR—IV

BY J. B. WHITEHEAD AND T. T. FITCH

I. Introduction

This paper describes the results of a series of investigations on the effects of pressure, temperature and density of gas upon the formation of the corona in air. It is largely an extension of work described in the second of this series of papers.

The study of the influence of temperature and pressure on corona-forming voltage was begun by Ryan in 1904. The influence of pressure in its relation to the size of conductor was shown in the second of this series of papers. The influence of temperature and pressure has been investigated also by Peek who has given an interesting empirical formula connecting critical corona intensity in air with pressure, temperature and size of conductor. The influence of pressure on critical corona intensity has been studied by Watson for the case of continuous voltage. The purpose of the present work has been the extension of the earlier investigations both as to range of pressure and size of conductor and also to obtain further information on the influence of temperature. Some observations were also made with carbon dioxide as the gas surrounding the conductor instead of air to see what part, if any, is played by the density of the gas.

The larger part of the work is the study of variation of critical or corona-forming intensity with pressure. For this work conductors varying from 0.438 to 0.950 cm. in diameter were used, and the pressure was varied from 5 to 110 cm. of mercury.

II. Review of Earlier Work on Pressure and Temperature

A brief review of earlier investigations on the variations of critical intensity with pressure and temperature will not be

out of place. Some other points, also, have such an intimate relation to these variations or at least to a study of them that they will be mentioned.

It was shown by Ryan[1] that for the one size of conductor which he used, the critical intensity is a linear function of the pressure from 40 to 90 cm. of mercury. A similar relation was shown to hold for variations with temperature between 21 and 93 deg. cent.

Watson published a set of experiments[2] in 1909 showing a linear relation between pressure and critical intensity for the case of continuous voltage. His range of pressure was from 36 to 76 cm. of mercury and of size of conductor from 0.07 to 0.95 cm. He also gave curves showing the amount of current passing.

In the earlier papers of this series numerous curves were given showing a linear relation between critical intensity and pressure from 38 to 100 cm. The conductors used ranged in diameter from 0.122 to 0.475 cm. Some experiments were also made showing a linear relation between critical intensity and temperature. Only one size of conductor was used. The range of temperature was from 8 to 41 deg. cent.

It has further been shown in these papers that:

The critical intensity is independent of free ionization, moisture content and velocity of the air.

The visual critical intensity is identical with that determined by an electroscope.

The critical intensity g for clean round conductors for a pressure of 76 cm. and temperature of 20 degrees may be expressed by the formula:

$$g = A + \frac{B}{\sqrt{D}} \qquad (1)$$

where A and B are constants and D is the diameter of the conductor. This formula is discussed in a later paragraph.

Peek[3] has given the results of a set of experiments on the variation of critical intensity with temperature showing practically a linear law between -20 and $+140$ deg. cent. He has also given a general formula covering the variations of critical

1. Ryan: *Conductivity of the Atmosphere at High Voltages*, TRANS. A. I. E. E., Vol. XXIII, 1904.
2. *Electrician*, Vol. LXIII, 1909.
3. Peek: *The Law of Corona*, TRANS. A. I. E. E., Vol. XXXI, 1912.

intensity with change of temperature and pressure for a tube and concentric conductor as follows:

$$g = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta\, r}}\right) \qquad (2)$$

where g is the critical intensity in kilovolts per cm., r is the radius of conductor and

$$\delta = \frac{3.92\,p}{273 + t}$$

p being the pressure in cm. of mercury and t the temperature centigrade. So far as we can find, the only statements he has given concerning the influence of pressure on the variation of critical intensity are a curve[4] giving observations on a 2.54-cm. conductor for pressures from 2 to 65 cm. and a table of values of δ and corresponding values of g in closing the discussion of his 1912 paper.[5] No description of his methods was given.

III. Present Work

The observations which are recorded in this paper were made in the spring of 1912. They aim to supply, in part, the lack of sufficiently extensive data on variation of critical corona intensity with pressure and size of conductor.

Apparatus and Equipment. For the pressure measurements a 20-cm. iron tube about 90 cm. in length was used. The ends were fitted with insulating caps about 18 cm. long. These caps were made of impregnated fibre, and served the double purpose of insulation and sealing for the variation of air pressure both above and below that of the atmosphere. A rotary air pump permitted evacuation of the tube to about five cm. of mercury in five minutes. Most changes of pressure could be made in a minute or two, but owing to numerous joints necessary for insulation purposes there was present some leakage, which necessitated a longer time to exhaust to the lowest pressure reached, and set the limit of about five cm. as the minimum.

A small glass window was placed in the tube for making visual observations of the corona, but during most of the work the gold leaf electroscope was used for detecting the point at

4. Peek: "Nature of Corona," *Gen. Elec. Review*, December, 1912.
5. Peek: *The Law of Corona*, Trans. A. I. E. E., Vol. XXX, 1912.

which corona begins. This method has been described in detail in the first of these papers, so no further description is necessary here. Fig. 1 shows the general arrangement of the apparatus. The beginning of corona is very sharply defined. A change of one per cent or less in the voltage will cause the time of complete discharge to change from about a half hour to five seconds. Any difference between the beginning of corona as observed by the eye and by the discharge of the electroscope is within this small error of observation.

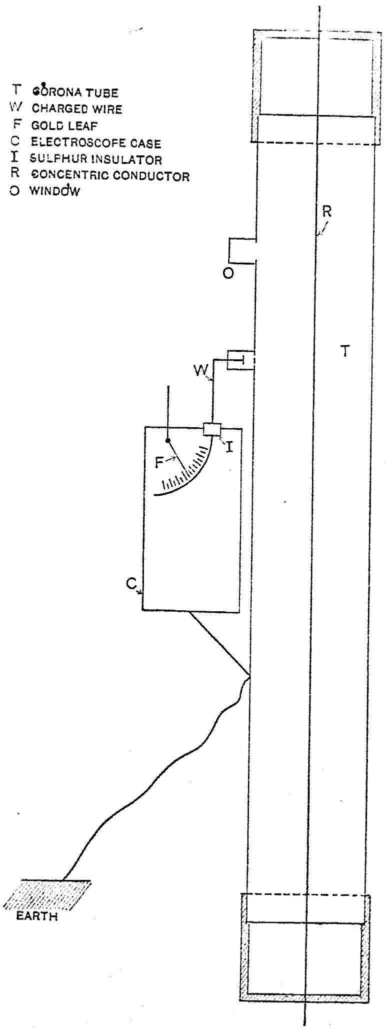


FIG. 1—ARRANGEMENT OF APPARATUS

The observations on the influence of temperature were made with a similar apparatus, except that the tube was in this case surrounded by a water jacket. Hand stirring of the water was found to be sufficient to keep the temperature of the air within the tube uniform to about two degrees. Only the smaller sizes of conductor could be used in this apparatus owing to spark-over troubles occasioned by the reduced size of outer tube. The heating was done by gas burners and ice was used for getting reduced temperature.

Source of Power. The power for all the experiments was drawn from a 10-kw., 100,000-volt transformer. The transformer was operated by a motor-generator set of 7.5 kw. capacity, the generator field being excited by a storage battery, resulting in good voltage control. All experiments were made at a frequency of 60 cycles. The transformer is provided with a

test coil giving 120 volts for 100,000 volts on the high-tension terminals as computed from the ratio of primary and secondary turns. This test coil was used entirely in making measurements of the voltage. All determinations of ratio of maximum to mean effective voltage were also obtained from this coil.

Ratio of Maximum to Mean Effective Voltage. For the purpose of checking the results this ratio was determined by two methods. The first makes use of the oscillograph, the second of a rotating contactor and the principle of the potentiometer.

The ratio was determined from the oscillograms by reading a number of ordinates, usually about 30 or 40 to a cycle. From these ordinates taken at equal distances the ratio of maximum to the square root of the mean square value was computed. The principal difficulty with this method is to obtain an oscillogram with lines sufficiently sharp and narrow.

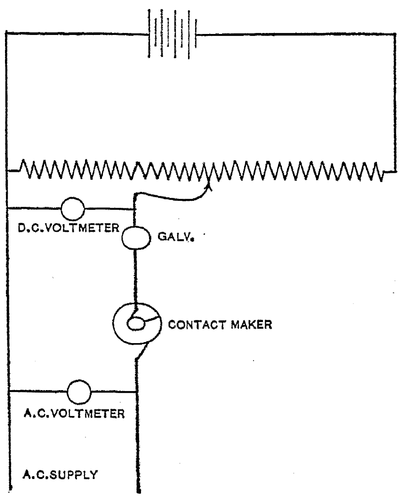


FIG. 2—METHOD OF MEASURING RATIO OF MAXIMUM TO MEAN EFFECTIVE VOLTAGE

The contactor method is indicated in Fig. 2, the contact wheel being placed on the generator shaft. In the actual apparatus a handle was provided for readily shifting the point of contact. By reference to the galvanometer the contact can be shifted until the closure occurs on the peak of the wave. Then the slider on the rheostat is moved until the galvanometer indicates zero deflection. The readings of the continuous and alternating voltmeters are then taken. The ratio of their readings in volts is the ratio desired, the direct-current voltmeter indicating the maximum voltage and the alternating-current voltmeter the mean effective value.

The chief difficulty with this method is to keep the source of alternating voltage sufficiently steady during the time necessary for an observation. A damped galvanometer of fairly high sensibility is required. Only the relative calibration of the voltmeters is necessary since the ratio is all that is required. The alternating voltmeter used was of the electrodynamometer

type and it was compared with the direct-current voltmeter by taking the mean of readings with reversed polarity.

Table I, of which Fig. 3 is a plot, gives the ratio of maximum to mean effective voltage for the various voltages on the test

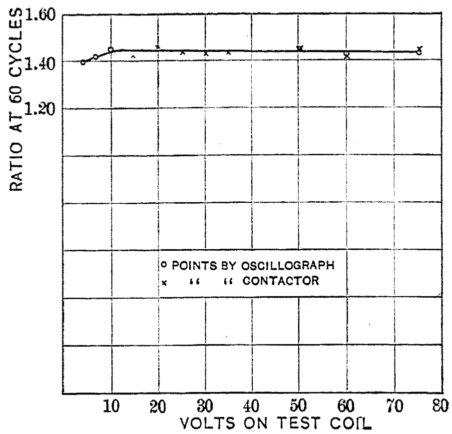


FIG. 3—RATIO OF MAXIMUM TO MEAN EFFECTIVE VOLTS. FROM TEST COIL OF 100,000-VOLT TRANSFORMER

coil of the transformer used in the experiments. The values taken from the curve were used in making reductions of readings on critical intensity.

Fig. 4 is a reproduction from a typical oscillogram.

TABLE I

Test coil volts	Ratio = $\frac{\text{Max.}}{\text{Mean eff.}}$		
	Contactor	Oscillograph	From curve
4		1.395	1.400
7		1.420	1.420
10		1.450	1.440
15	1.431		1.440
20	1.459		1.445
25	1.436		1.445
30	1.429		1.445
35	1.438		1.445
50	1.444	1.446	1.440
60	1.421	1.430	1.440
75	1.452	1.427	1.440

Variation of Critical Intensity with Gas Pressure. Fig. 5 shows the observed variation of critical corona voltage with pressure, while Fig. 6 shows the corresponding variation of critical intensity computed from the same observations. As mentioned before, nine conductors varying from 0.238 to 0.950 cm. in diameter were used. Above 30 or 40 cm. pressure the curves are nearly straight; the curvature being so slight as to be within the error of observation. They explain, therefore, the conclusion of the earlier paper that the relation between pressure and critical intensity is linear in this region.

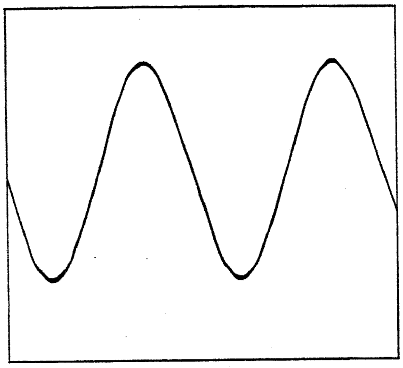


FIG. 4—TAKEN AT 60 CYCLES AND 60 VOLTS

We have used the expression

$$\frac{dv}{dr} = \frac{E}{r \log \frac{R}{r}}$$

for calculating the critical intensity in kilovolts per cm. from the observed critical voltage on the transformer test coil. E is the maximum voltage on the conductor obtained by taking into account the ratio of transformation of the transformer, and the ratio of maximum to mean effective voltage, while r and R are the radii of conductor and tube, respectively.

Table II gives a typical set of observations.

Several readings were taken at each pressure as shown in the readings for the last three pressures. The pressure was determined by use of a gauge or monometer. This method gives, of course, only the difference of pressure between that in the tube

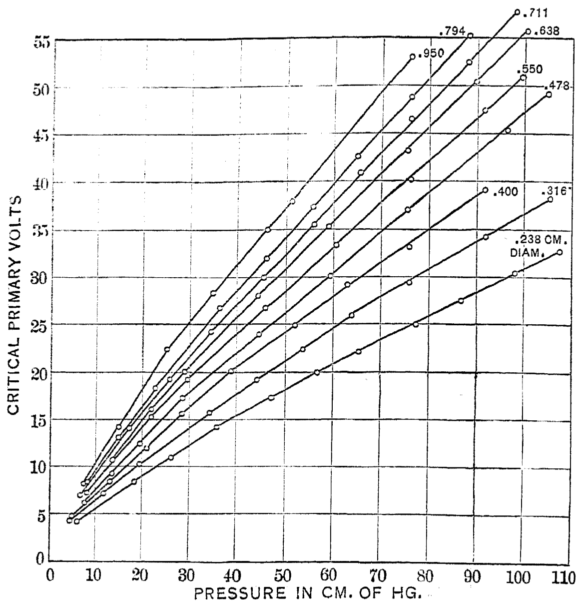


FIG. 5—OBSERVED VARIATION OF CRITICAL CORONA VOLTAGE WITH PRESSURE. TRANSFORMER RATIO = 833

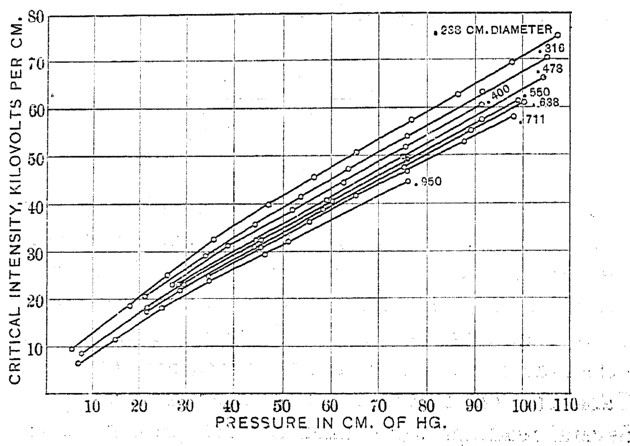


FIG. 6—VARIATION OF CRITICAL INTENSITY WITH PRESSURE AND SIZE OF CONDUCTOR AT 20 DEG. CENT.

and atmospheric. For this reason it was necessary to read the barometer to obtain the absolute pressure. The voltage was read by two Weston alternating-current voltmeters of suitable ranges connected to the test coil of the transformer, as stated. In taking readings the electroscope was first charged and then the voltage gradually raised till the electroscope was suddenly discharged, as shown by the fall of the gold leaf. Attention is called to the accuracy with which observations may be repeated.

TABLE II

Diameter of conductor 0.316 cm. Transformer ratio 833 $\dfrac{1}{r \log R/r} = 1.539$

Gauge readings mm. of hg.		Diff.	Temp. deg. cent	Barometer	Pressure mm.	Test coils volts	Ratio $= \dfrac{\text{max.}}{\text{eff.}}$	Critical kilovolts max.	Critical intensity kv. cm.
288	1000	712	18.2	760	48	4.5	1.40	5.2	8.0
316	960	644	18.2	760	116	7.2	1.42	8.5	13.1
348	915	567	18.2	760	193	10.3	1.44	12.3	18.9
361	910	549	19.8	756	207	10.9	1.44	13.0	20.0
365	909	544	19.8	756	212	11.2	1.44	13.4	20.6
431	846	415	19.8	756	341	15.7	1.44	18.9	29.1
484	799	315	19.8	756	441	19.3	1.44	23.2	35.7
530	750	220	19.8	756	536	22.4	1.445	27.0	41.5
592	710	118	19.8	756	638	25.5	1.445	30.7	47.2
					756	29.3	1.445		
			19.8	756	756	29.5	1.445	35.5	54.6
					756	29.5			
					756	29.3			
755	597	158			914	34.0	1.445		
755	597	158			914	33.9			
754	597	157	19.8	756	913	34.0		41.0	63.1
754	597	157			913	33.9			
849	554	295			1051	38.2			
850	555	295	19.8	756	1051	38.2	1.445	46.0	70.8
850	555	295			1051	38.2			
850	555	295			1051	38.2			

Empirical Formulas. As stated before, Peek has given the formula

$$g = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta\, r}}\right)$$

connecting the critical intensity g in kilovolts per cm. with pressure, temperature and radius of conductor. Fig. 8 shows

curves for three sizes of conductor for the temperature 20 deg. cent. As indicated, the circles are observed points while the full lines are plotted from the formula given above. It is seen that as the formula stands, it does not meet our observations very closely, though it gives a curve of the correct general form. By suitable changes in the constants the formula is brought into close agreement.

Fig. 9 is plotted from the formula

$$g = 33.6\,\delta\left(1 + \frac{0.235}{\sqrt{\delta\, r}}\right) \qquad (2)$$

The circles show the observed points as before. It is seen that with the formula so changed it represents the observations about

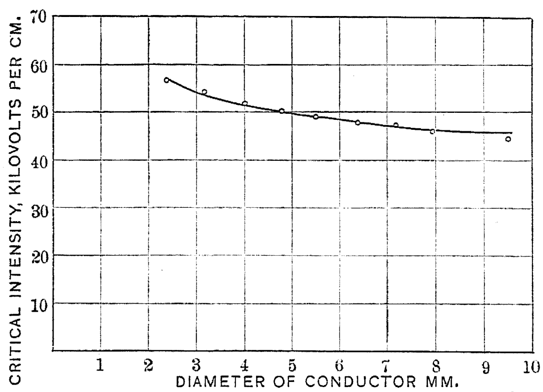


FIG. 7—VARIATION OF CRITICAL INTENSITY WITH SIZE OF CONDUCTOR AT 20 DEG. CENT. AND 76 CM. PRESSURE

as closely as the readings can be taken. This formula gives zero voltage for zero pressure provided r has a value greater than zero, which, of course, it has for any real case. As the present observations run only as low as 4 or 5 cm. pressure, they furnish no test on this point. Investigations are now under way to determine what becomes of the corona at very low pressures.

If in equation (2) the value of δ at 76 cm. pressure and temperature 20 deg. be substituted, the following formula is obtained:

$$g = 34 + \frac{11.2}{\sqrt{D}} \qquad (3)$$

This formula gives the variation of critical intensity with D the diameter of conductor at standard temperature and pressure.

The curve in Fig. 7 is a plot from this equation, while the circles are observed points. In the earlier work a formula of the same form but with different constants was given, namely:

$$g = 32 + \frac{13.4}{\sqrt{D}} \tag{4}$$

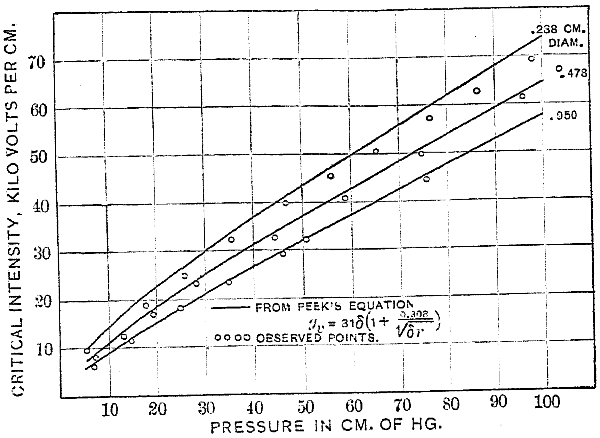


FIG. 8

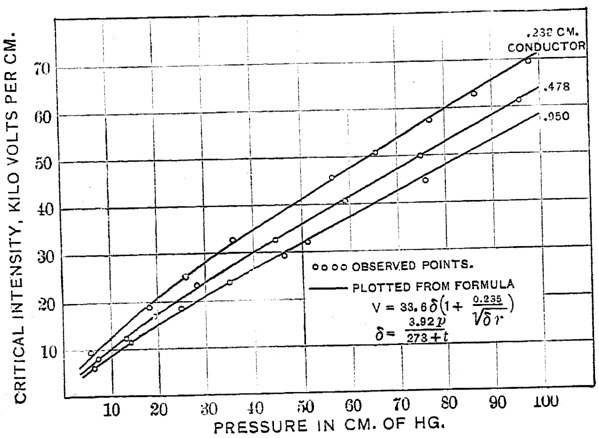


FIG. 9

The first constant of formula (**4**) is less than that of formula (**3**) while the second is greater, so the difference is largely one of curvature. What difference there is over the range of conductors observed is accounted for by a small discrepancy in the ratios of transformation of the transformers used in the earlier

experiments and in the present ones. It was found by trial in the earlier experiments that the indicated critical voltage with the 30,000-volt transformer with which those experiments were conducted was 54 kv. for a 0.345-cm. conductor and 52.4 for the 100,000-volt transformer which was used in the present set of experiments. These two differing values were obtained at the same time and with voltage from the same generator. Allowing for this discrepancy the present observations are brought into close agreement with the older values. As the purpose of this work is the investigation of the influence of density of gas on critical corona intensity, and as the above discrepancy does not affect the results relatively, its elimination has been left to a later date.

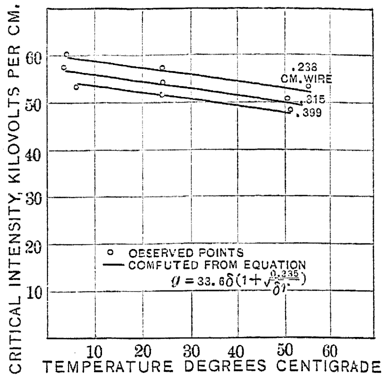


FIG. 10—VARIATION OF CRITICAL INTENSITY WITH TEMPERATURE AT 76 CM. PRESSURE

Variation of Critical Intensity with Temperature. The curves of Fig. 10 show the variation of critical corona voltage with temperature corrected to the pressure 76 cm. Table III gives the data from which the curves were plotted. The values computed are from the formula

$$g = 33.6\ \delta \left(1 + \frac{0.235}{\sqrt{\delta\ r}}\right)$$

TABLE III

Diameter of conductor	Temp. deg. cent.	Barometer	Test coil volts		Critical intensity	
			Read	Corrected	Obs.	Comp.
0.238	4.0	758	22.6	22.6	60.3	59.8
	24.3	760	21.5	21.5	57.5	56.6
	55.4	754	19.8	20.0	53.5	52.3
0.315	3.7	758	26.4	26.4	57.6	56.8
	24.2	760	25.0	25.0	54.3	53.4
	50.8	754	23.1	23.3	50.7	50.0
0.399	6.3	758	29.1	29.1	53.7	54.2
	24.2	760	28.1	28.1	51.8	51.3
	51.0	754	25.9	26.1	48.1	47.8

The diameter of tube used as outer conductor in these experiments was 10.5 cm. The curves in Fig. 9 are practically straight lines, as the range of temperature is not great enough to bring out any curvature. The agreement with the revised Peek equation is also very close here.

Influence of Density of the Medium on Critical Intensity. A simple calculation from the gas equation

$$pv = R\,T$$

shows that the pressure coefficient and temperature coefficient interpreted in terms of the change in volume of unit mass of gas are the same. In other words the critical corona intensity in air varies nearly as the density whether such change is produced by a change of pressure or temperature. This idea is implicitly stated in Peek's equation in his density factor. It must be remembered, however, that his definition gives only

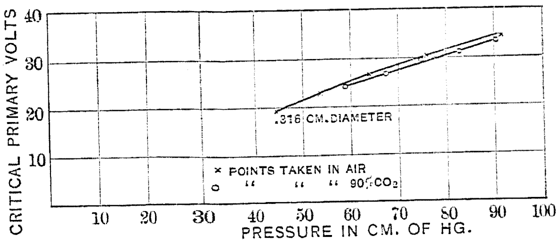


FIG. 11—EFFECT OF DENSITY OF THE MEDIUM ON CRITICAL INTENSITY

the relative density. With a view to the more definite investigation of the influence of density as the mass per unit volume we have made some interesting preliminary observations on the corona in a gas heavier than air.

In Fig. 11 are shown two curves of the variation of critical intensity with pressure, one in air and the other in a mixture of carbon dioxide and air, but containing about 90 per cent by volume of the former. Owing to leakage of the tube it was not possible to fill it with the pure gas. It is seen that there is little change due to the presence of the carbon dioxide, although its density is about 1.5 times that of air. It appears, then, from these experiments, that the variation of critical intensity does not, in fact, depend on the density, but is rather a function of the separation of the molecules of the gas, since according to the law of Avogadro the number of molecules in a given volume of gas is a

function of the pressure and temperature only, and does not depend on the nature of the substance. The indication from these curves then is that the relation of the electric intensity and corona formation is found in the average separation of the molecules. This is in fact a principal tenet of the theory of secondary ionization or ionization by collision as explaining all forms of spark discharge in gases. The opinion has been expressed in several places in this series of papers that the theory of second-

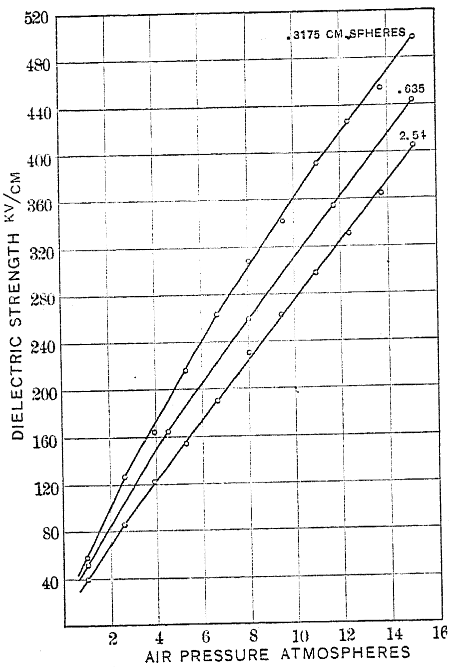


FIG. 12—SPARKING POTENTIALS BETWEEN SPHERES, BY WATSON

ary ionization offers the most promising explanation of corona formation.

IV. COMPARISON WITH RESULTS ON SPARKING POTENTIALS

Fig. 12 is reproduced from a paper by Watson on "The Dielectric Strength of Air."[6] The curves show the variation of the sparking potentials between spheres with variation of pressure. The pressures range from atmospheric upward, so that

6. *Jour. Inst. Elec. Engrs.*, Vol. XLIII, 1909.

they are not directly comparable with the pressures in the present set of corona experiments. From the work of other observers, however, it is known that the curves extend down toward the zero until they reach the so-called "critical pressure." Upon further reduction of pressure the curves turn sharply upward. These critical pressures vary with the length of spark gap, ranging from 3 to 0.3 mm. for spark gaps of 1 to 10 mm., respectively.[7]

It is seen by reference to the curves that their general shape is the same as for critical corona intensity. The chief question of interest in both cases is the departure from the linear law as the curvature is probably due to a common cause. By analogy with curves for sparking potentials it may be anticipated that the critical corona intensity may rise at very low pressures. It is well known that it is difficult to get the vacuum tube discharge at very high vacua.

The results obtained with corona in carbon dioxide were to be anticipated from Paschen's law. This law states that the sparking potential depends on the product of the pressure and the spark length. Curves plotted with products of pressure and spark length as abscissas and sparking potentials as ordinates are nearly the same for air and carbon dioxide but differ considerably for hydrogen. No attempt was made to try hydrogen as the medium surrounding the conductor in the present set of experiments owing to the presence of some leakage of the tube which might have resulted in the production of an explosive mixture. We wish to emphasize the simplicity of the corona apparatus as a method for studying the theory of gaseous conduction.

V. Discussion

As most of the observed laws of corona formation are in accord with the theory of ionization by collision, a brief statement of some of the fundamental experiments and conclusions of that theory will not be out of place.

When two parallel conducting plates are connected to a source of potential difference and the gas between them ionized by X-rays or radium, it is found that a current passes. This current increases at first as the potential difference is increased, but later attains a stationary value. No further increase of the current with increasing voltage is noted until a considerably higher voltage is reached when the current again increases rapidly with increasing voltage. The interpretation of this phenomenon is

7. "Conduction of Electricity through Gases," J. J. Thomson, 1906.

that the X-rays produce ions at a definite rate so that the current which can be produced by sweeping out all these ions has a limit. The stationary value of the current spoken of, marks this limit. When, however, the voltage becomes sufficiently high the ions attain a velocity which enables them to produce new ones by collision with neutral atoms. This is known as ionization by collision or secondary ionization. This theory of ionization by collision accounts for the order of magnitude of the critical corona voltage which in the limiting case of plane surfaces is approximately 30 kv. per cm. The mean free path of the electrons is about 6×10^{-5} cm. at 76 cm. pressure and 20 deg. cent., as has been shown by Townsend and others. This is about six times the mean free path of the molecules of the gas. For the ordinary sizes of conductors the voltage over a mean free path of an electron is about 2 volts. This indicates that the critical intensity is that which gives the ionizing voltage of about 10 volts[8] in a distance of five times the mean free path, or in other words some of the electrons having a free path of five or more times the average, start the corona.

The ionization theory fails as yet to show why the critical intensity varies with the size of conductor and why the variation of critical intensity with pressure does not follow a linear law. As has been frequently shown, the critical intensity rises quite rapidly as the size of conductor is reduced. The intensity in the gas falls away as $1/r$ where r is the distance from the center of the conductor, and from this it is seen that the intensity diminishes much more rapidly in the immediate neighborhood of a small conductor than a large one. Nevertheless, the diminution in a distance of five or ten mean free paths of an electron is negligibly small in any practical case.

The corona begins and ends at approximately the same voltage on the e.m.f. wave. This indicates that the rate of recombination of the ions is very great. It appears possible from this fact that the corona will not start until the intensity is high enough over some depth such as half a mm. on account of the great amount of recombination which goes on in the neighboring space, where the intensity is too low.

VI. Conclusions

1. The critical corona-forming electric intensity in air has been determined over the range of pressure from 5 cm. to 108 cm.

8. Bishop: *Physical Review*, Vol. XXXIII, 1911.

of mercury, for nine sizes of round conductor of diameters from 0.23 to 0.95 cm.

2. A few observations on the influence of temperature within the range of 5 deg. to 55 deg. cent. are also recorded.

3. The results are in substantial agreement with the empirical relation between electric intensity, pressure and temperature suggested by Peek.

4. Experiments with carbon dioxide indicate that the critical corona intensity is independent of the absolute density of the gas, but depends on the number and spacing of the molecules, in accord with the theory of secondary ionization.

BIBLIOGRAPHY

Steinmetz: *Dielectric Strength of Air*, TRANS. A. I. E. E., Vol. XV, 1898

Scott: *High Voltage Power Transmission*, TRANS. A. I. E. E., Vol. XV, 1898.

Ryan: *Conductivity of Atmosphere at High Voltages*, TRANS. A. I. E. E., Vol. XXIII, 1904.

Mershon: *High Voltage Measurements at Niagara*, TRANS. A. I. E. E., Vol. XXVII, 1908.

Balch: "80,000-Volt Transmission Line," *Jour. of Elec.*, 1904.

Brecht: "A 500,000-Volt Experimental Line," *Electrotechn. Anzeiger*, Vol. XXVI, 1909.

Lyndon: "The Corona and Design of High Tension Lines," *Elec. Review and Western Electn.*, Vol. LIV, 1909.

Watson: "Atmospheric Loss under Continuous Current," *Electrician*, September 3, 1909; February 11, 18, 1910.

"Dielectric Strength of Compressed Air," *Jour. Inst. Elec. Engr.*, Vol. XLIII, 1909.

Moody and Faccioli: *Experiments on Corona*, TRANS. A. I. E. E., Vol. XXVIII, 1909.

Kemp and Stephens: "Disruptive Voltage in Air," *Inst. Elec. Engr.*, Vol. XLIV, 1910.

Hayden and Steinmetz: *Disruptive Strength of Air*, TRANS. A. I. E. E., Vol. XXIX, 1910.

Whitehead: *The Electric Strength of Air, I, II, III*, TRANS. A. I. E. E., 1910, 1911, 1912.

Peek: *The Law of Corona and the Dielectric Strength of Air, I and II*, TRANS. A. I. E. E., 1911, 1912.

"The Nature of Corona," *G. E. Review*, December, 1912.

Görges, Weidig and Jaensch: "Experiments on Corona Loss," *Electrotechn. Zeitschr.*, 32, 1911.

Wecker: "Sparking Pressure under Commercial Conditions," *Zeitschr. Verins. Deutsch. Eng.*, 55, 1911.

West: *High Voltage Line Loss Tests*, TRANS. A.I.E.E., Vol. XXX, 1911.

Faccioli: *Tests of Losses on High Tension Lines*, TRANS. A. I. E. E., 1911.

Zickler: "Zur Berechnung der Koronaverluste," *Electrotechn. und Maschinenbau*, September 15, 1912.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 27, 1913.

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION

BY W. W. STRONG

Purpose and Experimental Apparatus

The purpose of the present investigation was to obtain the watt-voltage curves of corona discharge under certain conditions that are met in the process of precipitating fumes, dust and smoke electrically. Up to the present time the engineer has been mostly interested in the energy losses that occur on high-voltage transmission lines. In general this corona current is an alternating one taking place at comparatively low voltages. In the electrical method used to remove suspended dust, smoke and fumes from gases it is advantageous to use a unidirectional corona current at as high potentials as possible without sparking or arcing taking place. On high-voltage transmission lines the aim is to prevent corona discharge. In electrical precipitation the aim is to produce as copious a corona current as possible.

In the present work[1] the apparatus is that indicated in outline in Fig. 1. The transformer T (ratio of transformation 237) is supplied by 220-volt mains through a lamp resistance LR. A is an ammeter, V a voltmeter and W a precision wattmeter.

The transformer high-voltage terminals are connected to a rectifier R consisting of a commutator of an angular width of 30 deg. run at 1800 rev. per min. by a synchronous motor, the primary current being 60-cycle. This makes the effective angle of the commutator 60 deg. The rectifier apparatus was made so that the synchronous motor frame could be revolved through 100 deg. and clamped in any position while running at full speed.

1. See *Journ. Frank. Inst.*, Sept., 1912.

The position of the motor was read as being at 0 deg. when the motor frame was in a vertical position. When on open circuit the position of the motor for minimum sparking on the rectified side was 36 deg. from the vertical. The corona discharge takes place between the wire electrode *A E* and the grounded cylinder *C*. *B* is a blower for producing air currents in *C*. *G* is a furnace heated by natural gas or by coal. By using natural gas the air can be heated so that at *A E* its temperature may be 300 deg. cent. This " hot air " contains a large percentage of CO_2 and is in a state of greater or less ionization.

An illustration showing one of the precipitation chambers used in the present investigation is indicated in Fig. 2 in vertical section, and was designed by Prof. Nesbit and the writer. 11 and 12 are inlets for gases; *A E* is the active electrode and usually consisted of No. 20 wire; headers 13 and 14 serve to give rigidity to the five-inch cylinders 15; the cylinders are arranged in concentric circular series and in this chamber numbered 25, being 4 ft. (1.2 m.) in length; the header is made to fit tightly over the deposition box 10; 1 and 2 are large insulators connected by a rod 3, and to spoked rings 4 and 5 to which are fingers 6, and set screws 7 for centering and keeping the active electrodes stretched; 8 and 9 are supporting pieces that permit the whole system of electrodes to be raised off the settling chamber.

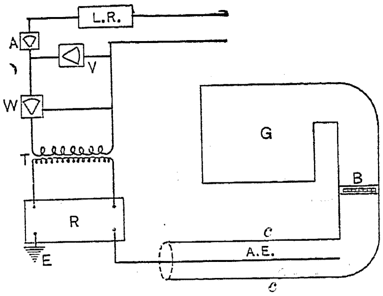


FIG. 1—DIAGRAM OF APPARATUS AND CONNECTIONS

When wires are used as active electrodes within metallic cylinders they are frequently set into vibration, a corona discharge taking place from the wire. This vibration is quite marked when the wire is not axially fastened and when the difference of electrical potential is almost equal to the sparking potential. The vibrations are much more easily excited and are much more violent when the corona is positive. This is to be expected, since the positive corona is very greatly affected by non-uniformity of the electric field. The positive corona brush discharge is entirely localized in the more intense portions of the electric field. On the other hand, the visible negative corona does not spread very far from the active electrode surface and is not easily modified

by the active electrode not being axially placed within the cylinder. This is one of the reasons why a negative corona is usually more effective in electrical precipitation than the positive corona.

The Nature of the Corona Discharge

It must be remembered that the corona discharge is only a special form of electrical discharge and is closely related to the point discharge, the various vacuum tube discharges, oscillatory and brush discharges, arcs, etc. Aubertin,[2] by using certain conditions of discharge, has observed the characteristic bright and dark regions in discharges at ordinary pressures by using a microscope. It is unfortunate that no study of the corona discharge has been made through a wide range of pressures, and it is quite possible that such a study would indicate the presence of an anode and cathode glow in the positive and negative coronas respectively. Such a glow or region of intense ionization would probably explain the fact that the break-down strength of air is greater for smaller wires, since the secondary ionization may take place in the gas near the metallic surface rather than at the metallic surface itself.

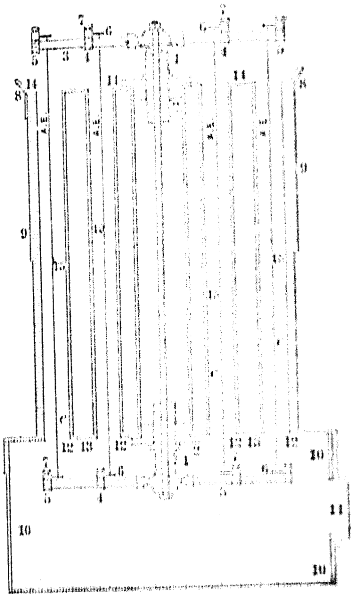


Fig. 2—Vertical Section through Precipitation Chamber

The ions produced by the corona discharge in pure gases such as oxygen and nitrogen possess a mobility of about a centimeter per second, the negative ions usually having a slightly greater mobility. There are many conditions, however, where ions have a much smaller mobility of about a thousandth part of that of "small" ions. Such ions are produced when hydrochloric acid acts on zinc, marble, etc.; when oxygen is prepared by heating potassium permanganate; when combustion takes place in flames, the burning of coal, etc. The presence of dust, fume particles, smoke,

2. C. R., 154, p. 874, 1912.

mist, vapor sprays, etc., results in ions of large mobility combining with these particles and forming ions of very small mobility. These ions may have as small a mobility as 0.0002 cm. per second or less, and will be called "large" ions. Large ions existing in the immediate neighborhood of flames have a diameter of about 0.1 μ (particles containing say 10^6 molecules), and exist in large numbers in free air (about 16,000 per cu. cm. under ordinary conditions).

The charged particles that one finds in hot gases, fumes, smoke, etc., consist of "simple" ions similar to those found in pure gases; "large" ions consisting of charged particles possessing a mobility of about 0.0001 cm. per sec. or less, the neutral particles being very small, usually invisible except in an ultramicroscope, and often called neutral centers; and charged dust, smoke, and fume particles of a size sufficiently large to be seen by the naked eye. In any gas the conditions will always be directed towards an equilibrium in the relative numbers of these three kinds of ions, the neutral centers and the dust particles.

Suppose a gas contains M neutral centers and is then subjected to an ionizing agent producing p positive and n negative simple ions per second. When equilibrium is reached there will be P positive and N negative large ions. In equilibrium the number of recombinations of neutral centers and small ions will be approximately equal to the disappearance of large ions, $d\,P/dt$ and dN/dt.

Broglie has shown that neutral centers are easily removed from gases by filtration through cotton. Neutral centers due to water dust are destroyed by heating to 250 deg. or 300 deg. cent. The ratio $P + N/M$ is very small. Broglie has succeeded in charging netural centers by the action of an electric field under certain conditions. Large ions often have a charge from 30 to 50 times as great as that of the elementary charge.

In electrical precipitation the presence of the simple and large ions has a very great effect upon the sparking and arcing potential. Some of the following data show this very clearly. For the most effective precipitation it is best to operate as near the sparking potential as possible. When a large amount of suspended matter is present in the gas the sparking potential is approximately the same as in air. An example illustrating this is the sparking potential between electrodes maintained at a constant difference of potential.

(Gap condition)		(Minimum spark gap length)
Room air		28 mm. gap length.
Flue gas	35 deg. cent.	35 " " "
" "	60 " "	35 " " "
" "	90 " "	37 " " "
" "	95 " "	45 " " "
Dense smoke	95 " "	30 " " "

The alternating corona is to be explained as depending on the properties of the positive and negative coronas. The positive and negative coronas are secondary ionization phenomena and may be influenced by the nature of the ions existing before the discharge commences.

Positive Current Corona Losses

In the data on positive and negative coronas it must be remembered that the reading instruments are on the primary side of the transformer; that about 60 deg. of the wave form is rectified; and that there are four small spark gaps in series in the secondary circuit. The length of these spark gaps was generally from one to about three mm. When any comparison is made between positive and negative corona the electrical and rectifier conditions are identical.

The energy consumption is measured at different voltages when one high-voltage terminal of the transformer is grounded and the other terminal is open. The open terminal is then connected to the active electrodes of the precipitation chamber and the increased loss of energy is assumed to go into the corona discharge. This is only approximately true.

Experiments have been performed for only a small range of gas velocity changes. In the experiments recorded in Table I a lamp resistance was placed in the primary of the transformer, lamps being gradually added in parallel in (*a*) and decreased in (*c*). In the case of the positive corona, the production of a draft did not increase the spark potential difference of the corona loss to any appreciable extent. This result is shown in the last reading of (*a*) and the reading of (*b*). In other words, the character of the discharge was but slightly changed by putting the air into motion.

The introduction of hot furnace gases causes a very considerable decrease in the sparking potential. In this instance the sparking potential was reduced from 30,600 to 28,500 volts. The sparks were of the "snapping" oscillatory type. The

number of lamps in the readings (1), (2), (3), (4), and (5) was the same. Readings (5) to (9) were made at practically the same potential, the amount of sparking decreasing. The sparks taking place at (5) consume almost as much energy as the corona itself. The positive corona loss appears to be slightly less in the hot gases than in room air. The energy loss due to the corona discharge and the transformer losses are given as "total." The

TABLE I

POSITIVE CORONA (ROTOR VERTICAL)

(a) Still air at room temperature.		Watts loss	
Secondary voltage	Primary amperes	Total	Corona
8,800	0.55	12	—
21,300	0.95	76	10
23,800	1.45	128	52
24,000	1.94	182	105 (?)
27,500	2.42	236	142
28,700	2.95	285	185
29,300	3.4	330	225
30,200	4.2	410	300
30,400 (1)	4.7	448	345
30,200 (2)	4.7	447	345
(b) Air velocity about 800 cu. ft. per min. Room temperature			
30,600 (3)	4.7	447	342
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
29,500 (4)	5.1 sparking	425	315
28,000 (5)	5.2 "	416	316
28,500 (6)	4.6 "	386	266
28,300 (7)	4.2 "	359	239
28,500 (8)	3.6 "	324	204
28,500 (9)	2.9 "	273	153
27,600	2.4	232	137
26,000	1.96	181	94
24,300	1.46	130	46
21,000	0.95	73	8

"total" loss minus the loss in the transformer and rectifier on open circuit (one terminal grounded) is given as the corona loss for 100 ft. (30.4 m.) of No. 20 wire in 5-in. (12.7-cm.) cylinders. The wires were cleaned only to the extent of careful brushing. The voltage is the effective volt reading of the primary multiplied by the ratio of transformation. The readings are of relative value only as the electromotive force wave is distorted from the sine form by the action of the rectifier.

Negative Current Corona Losses

From Tables I and III, which give comparable results for positive and negative corona, it will be seen that the ionization of a gas affects the two coronas differently. It was hoped that the properties of the alternating corona could be shown to be the additive effect (wattage loss curves, sparking potential, etc.) of the positive and negative coronas. On account of the irregularities introduced by the present form of rectifier this could not be

TABLE II

Positive Corona (Rotor 15 deg. from Vertical)

(a) Still air at room temperature		Watts loss	
Secondary voltage	Primary amperes	Total	Corona
21,800	1.0	79	—
27,300	1.42	129	35
31,000	1.8	178	63
33,500	2.23	220	85
34,600	2.63	257	115
36,300	3.0	293	130
36,800	3.4	319	150
37,200	3.55	345	165
38,000	5.0	388	198
(b) Air velocity about 800 cu. ft. per min. Room temperature			
38,600	4.5	400	200
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
36,500	4.6	360	195
36,300	4.15	337	166
36,000	3.6	319	160
35,600	3.1	290	135
35,000	2.65	253	103
33 200	2.25	219	80
30,700	1.85	178	63
27,200	1.4	130	35

done. A new form of rectifier is being devised to eliminate these effects as much as possible.

The following Table III gives the loss wattage due to a negative corona, the position of the rotor and the rectifier electrodes being the same as was the case when the data in Table I were taken. It is assumed that the fall in potential across the rectifier electrodes is the same as in the case of the positive corona. For given differences of potential the negative corona loss is less than the positive corona loss. In still air the sparking potential

is approximately the same for both coronas. The existence of a comparatively small air velocity permits the potential difference to be raised very considerably as is shown in (*b*).

The sparking potential difference for the hot furnace gas is about 4000 volts less than the value for air. Above 30,000 volts, the corona loss appears to be slightly greater in air than in the furnace gas.

Within the range of values used in these experiments it was found that the existence of a draft of air did not affect the wattage loss or the sparking potential of the positive coronas to any appreciable extent. The sparking potential is slightly greater when the air is in motion. The existence of even a small air

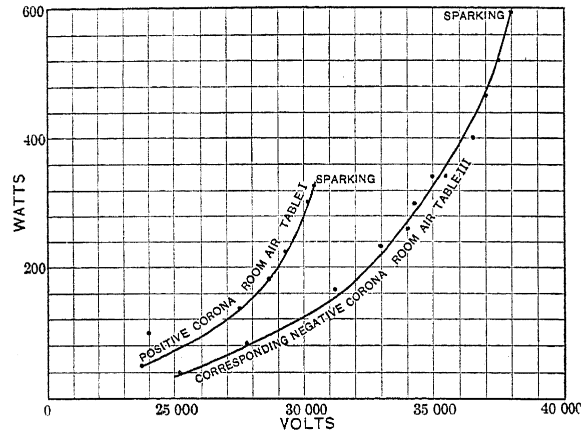


FIG 3—WATTS LOSS—ELECTRODES OF FIG. 2

velocity results in a very decided increase in the sparking potential of the negative corona. This results in the possibility of a much greater corona current density being obtainable in the process of precipitation when the active electrode is made negative. When warm ionized air is passed through the negative corona discharge the sparking potential is greatly reduced, the reduction in some instances being to the same or less value than that for still room air.

Assuming that the potential drop across the rectifier gaps is independent of the direction of flow of the current, it follows that for corresponding voltages the loss due to the positive corona is greater than that due to the negative.

High-Voltage Current Electrolysis

Some measurements were made of the electrolytic gas produced by the corona currents. The values obtained agreed approximately with the energy loss measurements. Alternating current corona begins to produce electrolysis when the voltage becomes

TABLE III

Negative Corona (Rotor Vertical)

		Watts	
Secondary voltage	Primary amperes	Total	Corona
(a) Still air at room temperature.			
8,800	0.5	12	8
21,600	0.95	76	45
25,300	1.38	130	85
27,800	1.8	184	125
29,700	2.2	234	165
31,200	2.58	281	198
32,500	2.87	325	234
33,000	3.2	364	260
34,000	3.47	400	298
34,300	3.7	440	334 Occasional sparking.
35,000	4.1	484	
(b) Air velocity about 800 cu. ft. per min. Room temperature.			
35,500	4.0	476	326
36,600	4.5	568	403
37,000	5.1	643	468
37,500	5.5	706	526
38,000	5.7	780	590 Sparking
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
35,000	5.0	578	392 Occasional sparking
34,000	4.35	492	352
33,300	3.65	411	280
32,500	3.35	377	251
31,600	3.1	333	213
30,600	2.7	291	136
29,300	2.3	238	130
27,300	1.88	186	91
24,700	1.33	130	50
21,300	1.0	78	10

sufficiently high or when short spark gaps are introduced into the circuit. Efforts are being made to make useful applications of these facts.

Summary

1. Since the negative corona is much more uniformly distributed about the active electrode, and on account of its greater

stability as regards sparking, the negative corona discharge is much more suitable than the positive for electrical precipitation. In the precipitation chamber described (capable of cleaning about 800 cu. ft. (22.6 cu. m.) of gas per min.) the negative corona consumes about 300 watts under the best conditions for precipitation.

2. Under similar conditions of the electrical circuit the loss due to the positive corona is slightly greater than that due to the negative corona at the same voltage.

3. For values of the electric field near the sparking potential the negative corona watt loss curve is flatter than the curve for the positive corona.

4. The positive corona loss in room air and ionized furnace gases is about the same. Increasing the air velocity affects the sparking potential and the corona loss but slightly.

5. Increasing the air velocity increases the sparking potential of a negative corona in ordinary air. The corona watt loss is considerably greater in hot ionized gas than in air.

6. The positive corona tends to go over to an oscillatory spark while the negative corona is more easily changed into an arc form of discharge.

7. Since the negative corona curve is the flatter and since larger negative corona currents can be obtained, the negative corona is much better adapted for electrical precipitation than the positive corona.

8. The presence of suspended matter in the gases does not affect the corona currents greatly.

9. The greater " dielectric strength " of air near small wires may be due to the corona discharge containing a " glow " region near the wire.

10. The presence of suspended matter in hot gases increases the sparking potential in these gases. This is probably due in part to the disappearance of the smaller ions. The presence of suspended matter in ordinary air decreases the sparking potential.

Application to a Smoke and Fume Indicator

Many of the effects of the presence of dust and smoke upon the high-tension electrical discharges are illustrated in the action of the smoke indicator. This instrument throws in an indicating circuit (such as a bell or red light circuit) whenever the smoke or fumes in a gas exceed a certain density. It consists of a high-voltage small-wattage (about 100 watts) transformer

in whose high-tension circuit are included a set of parallel spark gaps, one set of electrodes being placed in the flue gases and the other set being placed in air. The circuit conditions in the transformer are such that the discharge between the air electrodes is oscillatory and can be made to throw in circuits by the use of wireless telegraph methods.

The presence of dust, smoke and fumes increases the sparking potential of the flue gases so that when the intensity of this suspended matter exceeds a certain value, sparking takes place between the air electrodes. By regulating the length of the spark gaps the indicator circuit can be thrown on whenever the smoke density exceeds any given value.

In the absence of smoke, ordinary furnace gases permit the passage of a quiet violet flame discharge. These flames are ribbon-like and are forked. Under these conditions, the discharge is a maximum and the potential a minimum. As the amount of suspended matter is increased, this violet discharge gradually disappears, the current decreases and the potential increases. When the smoke is very dense the discharge becomes practically the same as in a non-ionized gas.

The explanation of this whole phenomenon is probably due to the ions produced in the furnace combining with the dust particles.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

(A Theory of Rupture)

BY F. W. PEEK, JR.

Visual Corona and Rupturing Energy

The apparently greater strength of air around small conductors was long attributed to a film of condensed air at the conductor surface having a greater relative effect for small conductors than large ones.

In *The Law of Corona—I**, as the result of extensive experiments it was shown that at atmospheric pressure (76 cm. barometer—25 deg. cent.) the maximum gradient at the surface of the wire when visual corona starts could be expressed by the equation

$$g_v = g_0\left(1 + \frac{0.301}{\sqrt{r}}\right) = 29.8\left(1 + \frac{0.301}{\sqrt{r}}\right) \tag{1}$$

The mathematical expression for the gradient at x cm. from the conductor surface is, where x is small,

$$g = \frac{e}{(r + x)\log_e s/r} \tag{2}$$

Then if $e = e_v$, the voltage at which visual corona starts, and $x = o$,

$$g_v = \frac{e_v}{r \log_e s/r} \tag{3}$$

*Trans. A. I. E. E., Vol. XXX, 1911, p. 1889.

Equating (**1**) and (**3**)

$$g_0 \left(1 + \frac{0.301}{\sqrt{r}}\right) = \frac{e_v}{r \log_e s/r}$$

or

$$g_0 = \frac{e_v}{(r + 0.301\sqrt{r}) \log_e s/r} = 29.8 \qquad (\mathbf{4})$$

From (**2**) it can be seen that g_0 is the gradient $0.301\sqrt{r}$ cm. from the conductor surface. This means that when corona starts, the *gradient* $0.301\sqrt{r}$ *cm. from the conductor surface is always constant*, g_0, independent of the size of the conductor or the spacing. See Fig. 1.

The theory advanced* for this *apparent* variation of the strength of air was:

Air has a constant strength g_0 for a given density, but a finite amount of energy is necessary to cause rupture or start corona. Hence rupture starts, not when the gradient is g_0 at the surface of the conductor, but only when the gradient is g_0 a finite distance from the surface; that is, the stress at the conductor surface must exceed the elastic limit g_0, or be increased to g_v in order to supply the necessary rupturing energy between the conductor surface and a finite distance in space ($0.301\sqrt{r}$ cm.) away where the stress is g_0 and breakdown occurs. The energy stored in this space may be called the rupturing energy. See Fig. 1.

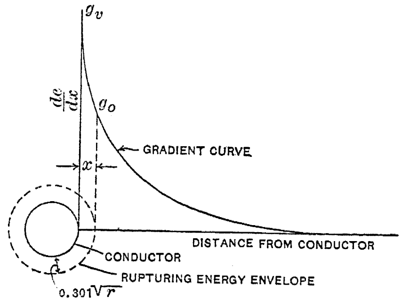


FIG. 1

Air Density. If g_0 is the strength of air at the standard density $\delta = 1$ (76 cm. – 25 deg. cent.), the strength at any other relative density should be

$$\delta \, g_0$$

where

$$\delta = \frac{3.92\, b}{273 + t}$$

Law of Corona and Dielectric Strength of Air—I, Trans. A. I. E. E. Vol. XXX, p. 1889.

The energy distance $a = 0.301 \sqrt{r}$ should also vary with δ if the rupturing theory given above holds, or

$$a = 0.301 \sqrt{r}\,\phi\,(\delta)$$

Then g_v should be written

$$g_v = g_0\,\delta \left(1 + \frac{0.301}{\phi\,(\delta)\,\sqrt{r}}\right)$$

This was shown to be the case in the *Law of Corona*—II,* or that

$$g_v = 31\,\delta \left(1 + \frac{0.301}{\sqrt{\delta\,r}}\right) \text{ kv. per cm.} \qquad (\mathbf{5})$$

therefore

$$a = 0.301 \sqrt{r/\delta}$$

It was also shown at this time that the effect was the same whether δ was varied by change of temperature or change of

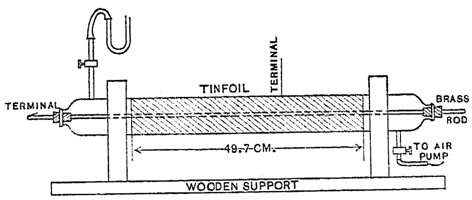


FIG. 2

pressure. The range of δ in these experiments was from 0.6 to 1.2, between which limits the curve between δ and g_v, though over the natural range of δ, is still very nearly a straight line. From (**5**), the form of which was predicted from theory, the curve shows a decided bend to $\delta = 0$ at the low values of δ.

Experiments were later made over the wide range of $\delta = 0.02$ to $\delta = 1$ in order to check equation (**5**) over this range as an additional check on the energy theory. The visual corona point was measured on polished brass rods in the center of a metal-lined glass cylinder. See Fig. 2.

The diameter of the cylinder was 7.36 cm., while the rod diameters ranged from 0.15 to 0.5 cm. In making observations the air was exhausted from the tube until the desired pressure was reached; voltage was then applied and increased until the starting point of corona was reached. The tube was " aired " out before

**Law of Corona and Dielectric Strength of Air—II*, TRANS. A. I. E. E., Vol. XXXI, 1912, p. 1051.

each reading. Some of the results of experiments, together with values calculated from the equation (**5**) given last year, are found in Tables I, II, and III. The results are shown graphically

TABLE I

DIAMETER OF BRASS ROD = 0.508 CM. = 0.2 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	δ $\frac{3.92\,b}{273+t}$	$g_v = \frac{e_v}{r\,(\log_e R/r)}$	g_v max. measured	g_v max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta r}}\right)$ kv. per cm.
1.7	1.392	23	0.0225	2,046	2.894	3.47
5.6	3,150	24	0.074	4,620	6.54	7.33
5.85	3,720	18	0.0788	5,460	7.72	7.63
8.8	4,610	24	0.116	6,780	9.60	9.90
13.5	6,580	18	0.182	9,660	13.68	13.55
16.0	7,470	18	0.216	10,960	15.50	15.27
28.2	11,390	18	0.38	16,740	23.66	23.2
38.1	14,470	18	0.513	21,260	30.06	29.1
49.5	17,700	18	0.667	26,000	38.60	35.75
61.5	20,700	18	0.828	30,400	43.00	42.7
75.7	24,535	18	1.019	36,000	50.92	50.25

in Figs. 3, 4 and 5, where the drawn curves are calculated, and the points are measured values. There is almost exact agreement throughout the range; any variation from the curve seems rather to be due to experimental error in reading pressure.

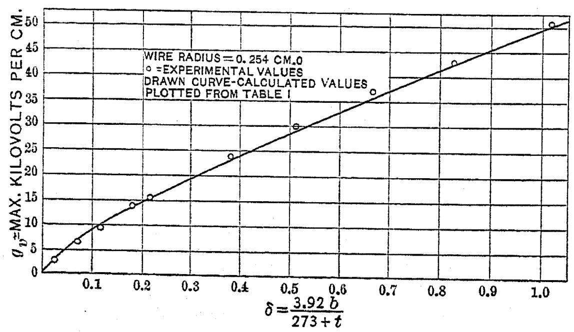


FIG. 3—CORONA AT LOW AIR DENSITIES

It is interesting to note that with two polished wires and the aid of the equation

$$*e_v = g_0\,\delta\,r\left(1+\frac{0.301}{\sqrt{\delta\,r}}\right)\log_e s/r$$

voltages anywhere may be measured by varying the spacing until corona starts and solving for e_v at this spacing.

TABLE II

DIAMETER OF BRASS ROD = 0.381 CM. = 0.150 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	$\delta = \frac{3.92\,b}{273+t}$	$g_v = \frac{e_v}{r\,(\log_e R/r)}$	g_v max. measured	g_v max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta\,r}}\right)$ kv. per cm.
5.33	2,880	27	0.0697	5,080	7.19	7.8
10.7	4,580	24	0.1412	8,090	11.45	12.40
11.2	4,920	27	0.1463	8,680	12.28	12.15
19.3	7,400	27	0.252	13,060	18.47	18.58
27.7	9,550	27	0.362	16,870	23.85	24.06
36.6	12,000	27	0.478	21,200	30.00	29.60
46.4	14,450	25	0.6125	25,500	36.07	35.70
47.0	14,600	27	0.614	25,800	36.50	35.80
55.7	16,300	27	0.728	28,800	40.75	40.75
60.0	17,760	25.5	0.792	31,350	44.30	43.5
66.0	18,400	27	0.867	32,500	46.00	46.75
75.0	21,100	25	0.997	37,250	52.7	52.25

ELECTRIC STRENGTH OF AIR FILMS

If a definite amount of energy is necessary to start rupture at a finite distance a from the conductor, with a surface gradient g_v,

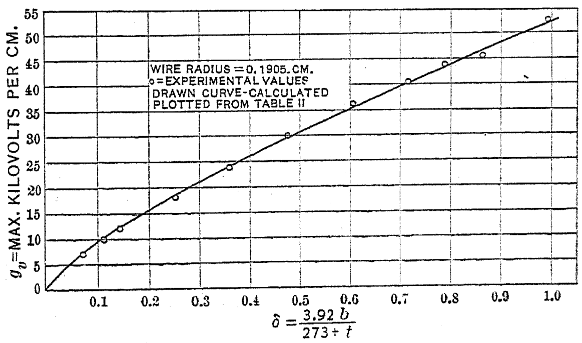


FIG. 4—CORONA AT LOW AIR DENSITIES

it is interesting to speculate what will happen at very small spacings or when the distance between conductor surfaces is of the order of a. See Fig. 6.

*Law of Corona and Dielectric Strength of Air—II. TRANS. A.I.E.E., Vol. XXXI, 1912, p. 1051.

As the free "energy storage" or "accelerating distance" is limited, a greater force or gradient should be required, provided the energy theory is true, when the distance between the conductors

TABLE III

DIAMETER OF BRASS ROD = 0.254 CM. = 0.1 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	δ $\frac{3.92\,b}{273+t}$	$g_v = \frac{e_v}{r\,(\log_e R/r)}$	g_v max. measured	g_v max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta\,r}}\right)$ kv. per cm.
4.9	2,490	22	0.0651	5,800	8.20	8.81
7.4	3,175	21	0.0987	7,400	10.45	11.27
10.3	3,925	21	0.1373	9,150	12.93	13.96
23.7	7,500	21	0.316	17,470	24.70	24.54
38.0	10,600	21	0.507	24,700	34.90	34.40
49.9	13,100	20.5	0.666	30,530	43.20	42.00
62.75	15,550	20.5	0.838	36,260	51.30	50.00
76.5	18,000	20.0	1.023	42,000	59.45	58.25

approaches a (see Fig. 6 (b) and (c)). Experiments were made to determine this, using spheres as electrodes. The ideal electrodes for this purpose would be concentric cylinders, but the use of these, as well as parallel wires, at small spacing seemed impracticable.

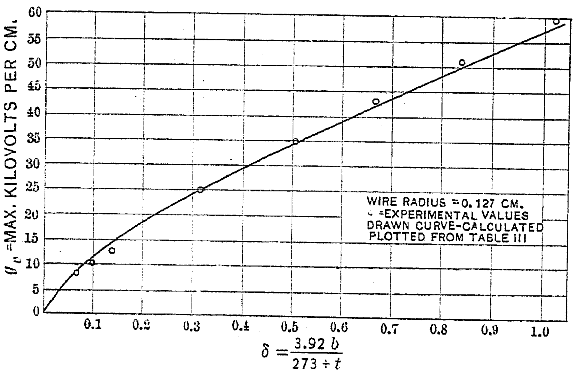


FIG. 5—CORONA AT LOW AIR DENSITIES

Spark-over and corona curves were made on spheres ranging in diameter from 0.3 cm. to 50 cm. and spacings from 0.0025 cm. to 50 cm. This discussion applies only to spacings up to $2R$ where corona can not yet form.

In these tests a 60-cycle sine-wave voltage was used. For the small spacing, the spheres were placed in a very rigid stand. One shank was threaded with a fine thread, the other was non-adjustable. In making a setting the adjustable shank was screwed in until the sphere surfaces just touched, as indicated by completing the circuit of electric bell and single cell of dry battery. A pointer at the end of the shank was then locked in place, after which the shank was screwed out any given number of turns or fraction of turns, as indicated on the stationary dial. For larger spacings other stands were used. Care was taken that surrounding objects were far removed from the spheres, to prevent distortion of the field.

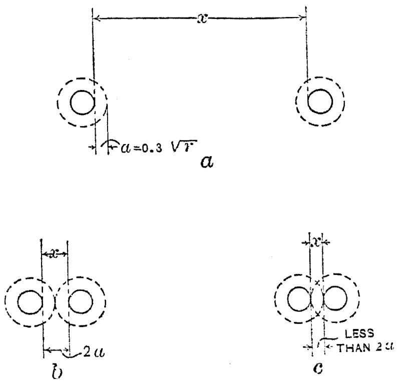


FIG. 6

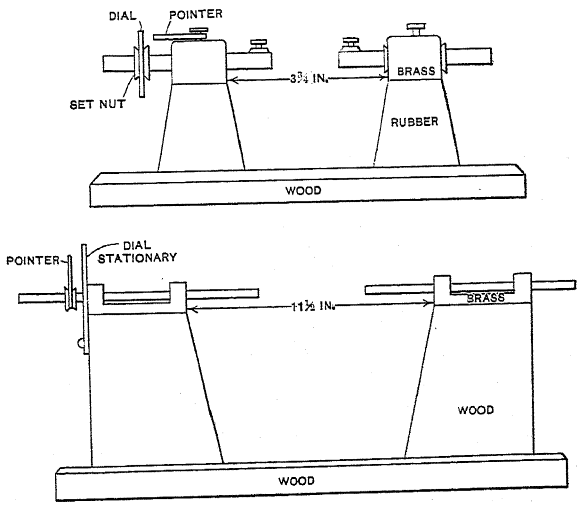


FIG. 7—SPECIAL SPARK-GAP STANDS FOR SPHERES

A typical spark-over-spacing curve, and corona-spacing curve, is shown in Fig. 8. Theoretically, up to a spacing of 2 R, corona cannot form and spark-over must be the first evidence

of stress, or, in other words, corona and spark-over are the same. Practically, corona cannot be detected until a spacing of 8 R is reached. This is because up to this point the difference between the corona starting point and the spark point is very small. Above 8 R the spark-over curve approaches a straight line, as in the case of the needle gap curve. The corona curve above 4 R and the spark-over curve below 4 R are apparently continuous. The gradient curve Fig. 9 is calculated from the voltage curve Fig. 8. Where the spacing X is less than $0.54\ \sqrt{R}$ the gradient increases slowly at first and then very rapidly with decreasing spacing. Between $X = 0.54\ \sqrt{R}$ and 2 R the gradient is very nearly constant. Above about 3 R spacing the gradient apparently increases. This apparent increase is probably due

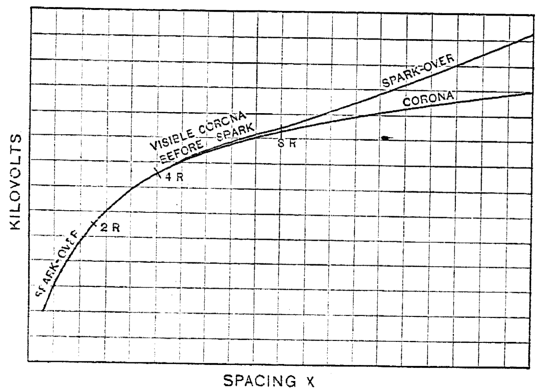


FIG. 8

to the effect of the shanks, etc., which becomes greater as X is increased. The effect of the shanks is to distribute the flux better on the sphere surface, and can not be taken account of in the equation for gradient. This was shown experimentally by using different sizes of shanks at the larger spacing. Thus when the spacing is greater than 3 R the sphere is not suitable for studying the strength of air, as the gradient can not conveniently be calculated. It is, therefore, not a suitable electrode for studying corona over any great range.

The maximum gradient at the surface of a sphere, (non-grounded), may be calculated from the equation

$$g = \frac{E}{X} f \tag{6}$$

Where X is the spacing between the nearest surfaces of the spheres, and E the voltage

$$f = 1/4 \left(\frac{X}{R} + 1 + \sqrt{\left(\frac{X}{R} + 1\right)^2 + 8} \right)^*$$

When one sphere is grounded the gradient is theoretically:

$$g = \frac{E}{X} f_1$$

where

$$f_1 = \frac{1}{2} \left\{ \frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 4} \right\}$$

Practically, however, the effects of the shanks, etc., for the grounded case require a value f_0 which we have determined experimentally. The case of one sphere grounded is not considered here.

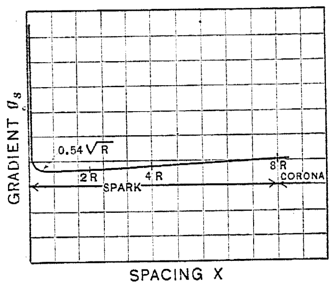


FIG. 9

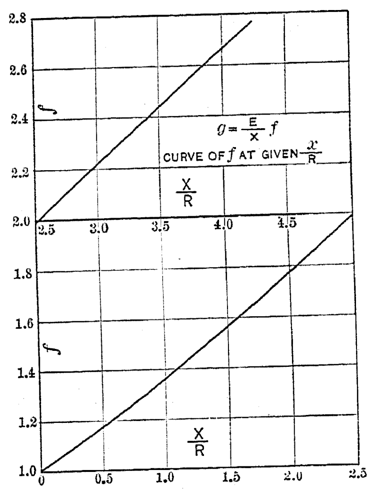


FIG. 10—FOR NON-GROUNDED SPHERES

The gradient for the non-grounded case may be conveniently calculated by use of the curve Fig. 10. The gradient on the line connecting sphere centers at any distance a from the sphere surface may be calculated from the complicated equation

$$g_a = \frac{E}{X} \left\{ \frac{2\, x^2 \,[x^2\,(f+1) + 4\,(X/2 - a)^2\,(f-1)]}{[x^2\,(f+1) - 4\,(X/2 - a)^2\,(f-1)]^2} \right\}^{\dagger} \qquad (7)$$

*See G. R. Dean, *G. E. Review* March, 1913. Russel—*Philosophical Mag.* 1906.

†G. R. Dean—*G. E. Review*, March, 1913. *Physical Review*. Dec. 1912 and April 1913.

Some of the experimental values are given in Tables IV, V, VI, VII, VIII, IX. Typical voltage gradient curves are shown in Figs. 11, 12, 13 and 14.

TABLE IV

STEEL SPHERE $R = 0.158$ CM. DIAM. = 1/8 IN.

X-Spacing		e_{eff}	δ	e_{max}	g_{max}	
in.	cm.	kv. read	$\frac{3.92\,b}{273+t}$	$\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	$\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.358	1.009	0.502	199.0	0.01598
0.002	0.00508	0.515	1.009	0.722	143.5	0.03196
0.003	0.00762	0.646	1.009	0.907	121.0	0.04794
0.004	0.01016	0.770	1.000	1.089	109.5	0.06392
0.005	0.0127	0.9235	0.9985	1.3085	105.7	0.0799
0.010	0.0254	1.440	0.997	2.045	85.0	0.1598
0.020	0.0508	2.150	0.984	3.090	67.5	0.3196
0.040	0.1016	3.475	0.984	5.000	60.2	0.6392
0.075	0.1905	5.840	0.9965	8.300	62.75	1.1985
0.100	0.254	7.065	0.9965	10.035	63.4	1.598
0.200	0.508	10.545	0.9840	15.170	68.85	3.195
0.300	0.762	12.070	0.992	17.200	68.8	4.793
0.400	1.016	13.465	0.9965	19.135	71.95	6.39
0.500	1.27	14.245	0.9965	20.14	73.075	8.00

TABLE V

STEEL SPHERES $R = 0.555$ CM. DIAM. = 7/16 IN.

X-Spacing		e_{eff}	δ	e_{max}	g_{max}	
in.	cm.	kv. read	$\frac{3.92\,b}{273+t}$	$\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	$\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.384	0.995	0.545	215.3	0.00458
0.002	0.00508	0.546	0.995	0.775	153.0	0.00916
0.003	0.00762	0.692	0.995	0.982	129.4	0.01374
0.004	0.01016	0.787	0.9995	1.1125	110.25	0.01832
0.005	0.0127	0.847	0.9995	1.209	96.0	0.0229
0.010	0.0254	1.160	0.993	1.653	66.1	0.0458
0.020	0.0508	2.030	0.993	2.895	58.7	0.0916
0.040	0.1016	3.430	0.993	4.890	51.2	0.1832
0.075	0.1905	5.750	0.993	8.200	48.2	0.344
0.100	0.254	7.160	0.986	10.280	46.9	0.458
0.200	0.508	12.400	0.986	17.800	46.4	0.916
0.300	0.762	17.000	0.992	24.250	48	1.374
0.400	1.016	20.500	0.992	29.250	49	1.832
0.500	1.270	23.400	0.992	33.400	49.7	2.29

TABLE VI

BRASS SPHERES $R = 1.27$ CM. DIAM. = 1 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\, b}{273 + t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}\, f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.387	1.01	0.542	213.4	0.002
0.002	0.00508	0.608	1.01	0.852	168.0	0.004
0.003	0.00762	0.712	1.01	0.998	131.0	0.006
0.004	0.01016	0.757	1.01	1.060	104.7	0.008
0.005	0.0127	0.808	1.01	1.132	89.5	0.01
0.010	0.0264	1.310	1.0095	1.836	72.72	0.02
0.020	0.0508	2.160	1.011	3.020	60.25	0.04
0.040	0.1016	3.520	1.005	4.950	50.0	0.08
0.075	0.1905	5.680	1.005	8.000	44.0	0.15
0.100	0.254	7.120	1.005	10.020	42.25	0.20
0.200	0.508	12.670	1.005	17.81	39.9	0.40
0.300	0.762	18.00	1.005	25.34	40.2	0.60
0.400	1.016	22.87	1.008	32.35	40.75	0.80
0.475	1.205	26.15	1.008	36.70	41.1	0.95

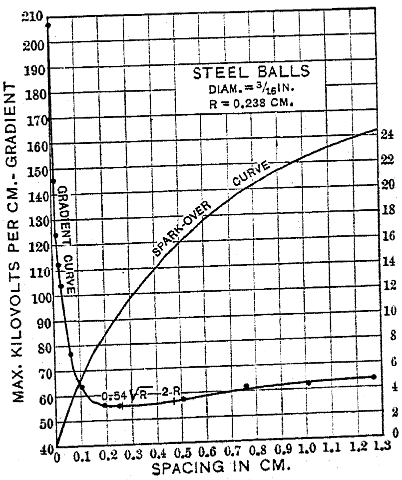


FIG. 11

TABLE VII

BRASS SPHERES $R = 3.33$ CM. DIAM. $= 2\frac{5}{8}$ IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273 + t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00245	0.3625	1.0285	0.4975	196.05	0.000763
0.002	0.00508	0.531	1.0305	0.7295	143.65	0.001525
0.003	0.00762	0.654	1.027	0.8995	118.15	0.002285
0.004	0.01016	0.7755	1.0265	1.0685	105.2	0.00305
0.005	0.0127	0.8447	1.0165	1.1717	92.312	0.00382
0.010	0.0254	1.070	0.998	1.518	60.0	0.00764
0.020	0.0508	1.857	1.002	2.620	51.8	0.01528
0.040	0.1016	3.275	1.002	4.620	45.95	0.03056
0.075	0.1905	5.430	1.002	7.660	41.0	0.05730
0.100	0.254	6.920	1.002	9.770	39.5	0.0764
0.200	0.508	12.400	1.002	17.500	36.26	0.1528
0.300	0.762	17.700	1.002	25.000	35.4	0.2292
0.400	1.016	22.700	1.002	32.000	34.8	0.3056
0.500	1.27	27.750	1.002	39.2000	34.95	0.382

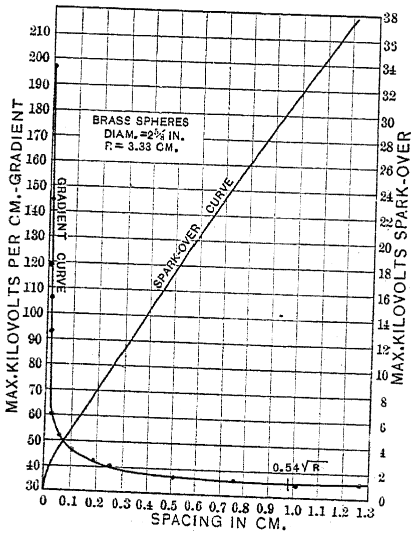


FIG. 12—PLOTTED FROM TABLE VII

TABLE VIII

BRASS SPHERES R = 6.25 CM. DIAM. = 4 15/16 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273+t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.378	0.993	0.538	212.0	0.000406
0.002	0.00508	0.475	0.992	0.678	133.3	0.000812
0.003	0.00762	0.590	0.992	0.841	110.4	0.00122
0.004	0.01016	0.710	0.996	1.008	99.3	0.00162
0.005	0.0127	0.833	1.006	1.1695	92.1	0.00203
0.010	0.0254	1.230	1.008	1.725	68.0	0.00406
0.020	0.0508	1.92	1.021	2.660	52.5	0.00812
0.040	0.1016	3.29	1.019	4.57	45.2	0.01624
0.075	0.1905	5.55	1.019	7.72	40.9	0.03042
0.100	0.254	7.02	1.022	9.72	38.8	0.0406
0.200	0.508	12.53	1.022	17.35	35.1	0.0812
0.300	0.762	17.73	1.022	24.55	33.62	0.1218
0.400	1.016	22.9	1.021	31.70	33.0	0.1624
0.500	1.27	27.85	1.021	38.58	32.5	0.2030

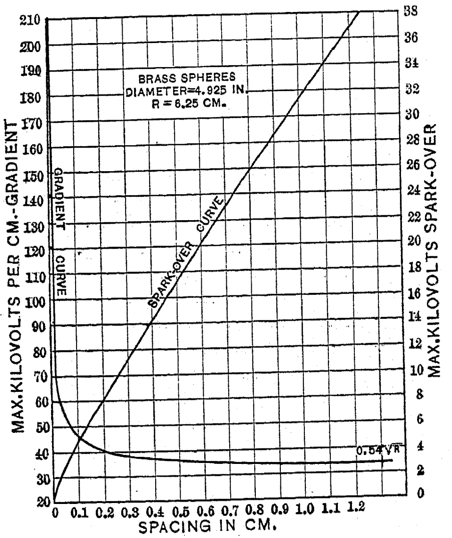


FIG. 13—PLOTTED FROM TABLE VIII

TABLE IX

BRASS SPHERES R = 12.5 CM. DIAM. = 9.84 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273+t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}f$ kv. per cm.	$\frac{X}{R}$
0.005	0.0127	0.8076	1.0226	1.1156	87.9	0.00101
0.010	0.0254	1.22	1.021	1.689	66.53	0.00203
0.020	0.0508	2.0506	1.0313	2.8396	55.9	0.00406
0.040	0.1016	3.3876	1.0223	4.683	46.2	0.00813
0.100	0.254	7.026	1.020	9.750	38.61	0.02032
0.200	0.508	12.54	1.0116	17.445	34.82	0.04064
0.300	0.762	17.91	1.016	24.92	33.5	0.06096
0.400	1.016	22.825	1.0103	31.765	32.05	0.08128
0.500	1.27	27.63	1.0103	38.67	31.53	0.1016
1.000	2.54	53.0	1.000	74.9	31.6	0.2032
1.500	3.81	75.3	1.000	106.3	30.9	0.3048
2.000	5.08	96.4	1.000	136.2	30.5	0.4064
2.500	6.35	117.4	1.000	166.0	30.7	0.5080
3.000	7.62	139.2	1.000	196.9	31.2	0.6096
3.500	8.89	158	1.000	223.4	31.3	0.7112
4.000	10.16	174.9	1.000	247	31.0	0.8128
4.500	11.43	190.8	1.000	269.5	31.0	0.9144
5.000	12.70	203.6	1.000	287.2	30.8	1.016

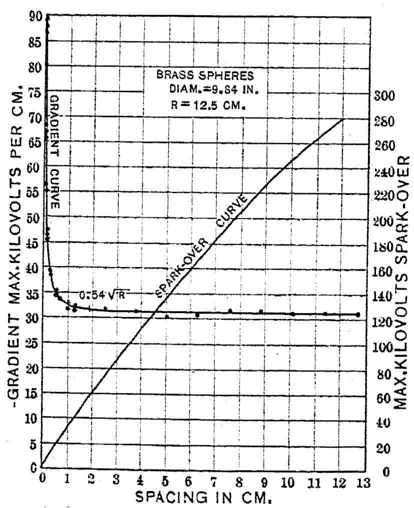


FIG. 14—PLOTTED FROM TABLE IX

TABLE X

Radius cm. R	Spacing cm. X Where g_s begins to increase	g_s max. kv. per cm. Constant part of curve	g_s max. kv. per cm. Average between $0.6\sqrt{R}$ and $3R$
0.159	0.18	63.8	
0.238	0.25	55.6	
0.356	0.26	51.4	
0.555	0.40	46.9	
1.27	0.51	39.9	42.5
2.54	0.85	36.8	38.4
3.33	0.95	34.8	37.1
6.25	1.30	32.5	33.5
12.5	2.0	31.3	31.3

$$g_s = 27.2\left(1 + \frac{0.54}{\sqrt{R}}\right)$$

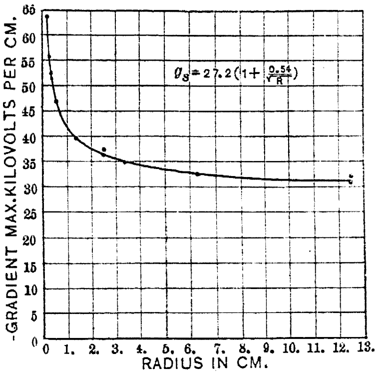


FIG. 15—PLOTTED FROM TABLE X

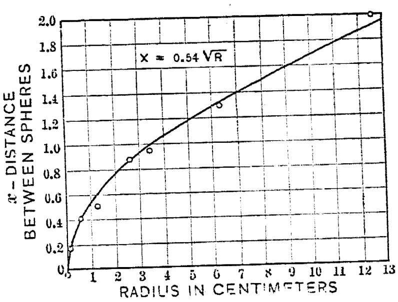


FIG. 16—PLOTTED FROM TABLE X

In Table X are tabulated for different sizes of spheres the spark-over gradients at constant part of curve, the average gradients between $X = 0.54\ \sqrt{R}$ and $X = 3\ R$, and the approximate minimum spacing at which the gradient begins to increase in value. The gradient-radius curve is plotted in Fig. 15. This curve is very closely given by the equation

$$g_s = g_0\left(1 + \frac{k}{\sqrt{R}}\right) = 27.2\left(1 + \frac{0.54}{\sqrt{R}}\right)^* \qquad (8)$$

which has exactly the same form as the similar curve for cylinders. The values of g_0 is, however, lower than for the balanced field of a wire in a cylinder.

*This is given for theoretical reasons rather than for exact practical calculations.

For a wire in a cylinder $g_0 = 31$
For parallel wires $g_0 = 30$
For spheres $g_0 = 27 - 28$

It is probable that the true strength of air is 31 kv. per cm. as represented by the balanced field; it is apparently less for parallel wires due to unbalanced field, and the apparent value is still less for spheres where the field is unbalanced to a still greater extent.

The curve between the sphere radius and the *approximate* minimum spacing below which the gradient begins to increase is plotted in Fig. 16 from Table X. The curve is represented by the equation

$$X = 0.54 \sqrt{R} \tag{9}$$

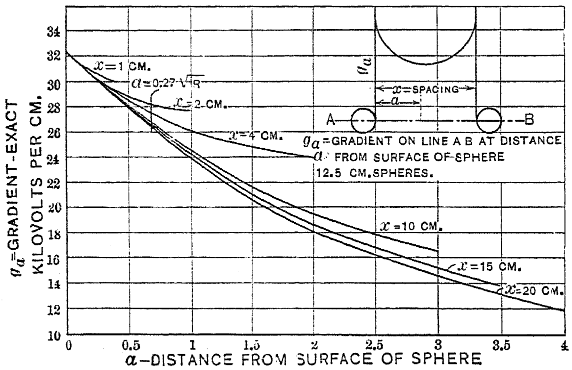


FIG. 17—CALCULATION OF GRADIENT BETWEEN SPHERES

which means that when the spacing is less than $0.54 \sqrt{R}$ the gradient increases in value, at first slowly, then very rapidly.

It is now interesting to investigate the meaning of equation (8). In Figs. 17 and 18 the exact gradient is plotted from equation (7) for different distances from the sphere surface on the line connecting the centers, and at given spacings, as indicated by the small diagram in the upper corner of the figure.

It is seen that for small distances from the sphere surface the curves for the different spacings fall together. Over this small range the gradient g_a at any point a cm. from the sphere surface on the center line may be found

$$g_a \simeq \frac{E}{R + 2a} \left(\frac{R}{X}\right) f \tag{10}$$

The only excuse for using this approximation, which holds only for very small values of a and is only true when $a = 0$, is that (**7**) is too complicated to handle. The error due to this approximation is shown in Table XI. Then

$$g_s = \frac{E_s}{X} f = \frac{E_s}{R}\left(\frac{R}{X} f\right) \quad \text{Exact mathematical} \tag{6}$$

$$g_s = g_0\left(1 + \frac{k}{\sqrt{R}}\right) \quad \text{Experimental for approximately constant part of curve.} \tag{8}$$

$$g_a \cong \frac{E}{(R+2\,a)}\left(\frac{R}{X} f\right) \quad \text{Approximate mathematical} \tag{10}$$

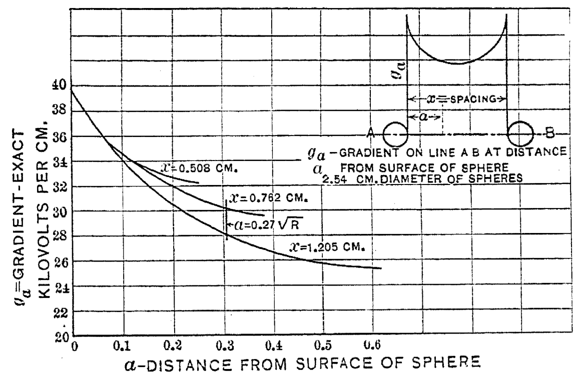


FIG. 18—CALCULATION OF GRADIENT BETWEEN SPHERES

Equating equations (**6**) and (**8**)

$$\frac{E_s}{R}\left(\frac{R}{X} f\right) = g_0\left(1 + \frac{k}{\sqrt{R}}\right)$$

$$g_0 = \frac{E_s}{(R + k\sqrt{R})}\left(\frac{R}{X} f\right)$$

which is the same form as (**10**), or which means that at a distance

$$\frac{k\sqrt{R}}{2} = \frac{0.54\sqrt{R}}{2} = 0.27\sqrt{R}\,\text{cm.}$$

from the sphere surface the gradient at rupture is always approximately constant, and is g_0. Breakdown must take place at approximately $a = 0.27 \sqrt{R}$ cm. from the sphere surface; therefore at the spacing $2a = 0.54 \sqrt{R}$ the gradient begins to increase. This is approximately so, as shown in Fig. 16 and equation (**10**). The increase is slow at $X = 2a$ but becomes very rapid at $X = a$. Looking at Fig. 17, it is seen that at $a = 0.27 \sqrt{R}$ the gradient

TABLE XI

$R = 1.27$ cm.

ENERGY DISTANCE $a = 0.27 \sqrt{R} = 0.3$ cm.

a	g_a Exact	g_a Approx.	X
0	39.9	39.9	0.76
0.1	34.6	34.0	0.76
0.2	31.9	30.0	0.76
0.4	29.7	24.1	0.76
0	39.9	39.9	1.21
0.1	34.2	33.4	1.21
0.2	30.5	29.5	1.21
0.4	26.5	23.7	1.21
	$R = 12.5$ cm.		
	ENERGY DISTANCE $a = 0.95$ CM.		
0	31.3	31.3	4
0.2	30.3	30.3	4
0.4	29.5	29.4	4
0.6	28.6	28.5	4
0.8	28.3	27.7	4
1.0	27.5	26.9	4
0	31.3	31.3	10
0.2	30.3	30.3	10
0.4	29.5	29.4	10
0.6	28.6	28.7	10
0.8	28	27.7	10
1.0	27.5	26.9	10

is not exactly constant for different spacings; that is, the curves do not fall together. This means that g_s and k in equation (**8**) cannot be *exactly* constant for a given radius but must also be a function of X.* This is experimentally shown to be the case.

Application of the Electron Theory

The electron theory may also be very well applied in agreement with the above, as has been already pointed out. Briefly:

When low potential is applied between two conductors any

*See footnote page 1781.

free ions at the surface are set in motion. As the potential and, therefore, the field intensity or gradient is increased, the velocity of the ions increases. At a gradient of $g_0 = 31$ kv. per cm. ($\delta = 1$) the velocity of the ions becomes sufficiently great over the mean free path to form other ions by collision with molecules. This gradient is constant, and is called the dielectric strength of air. When ionic saturation is reached at any point the air becomes conducting, and glows, or there is corona or spark.

Applying this to a wire in the center of a cylinder. When a gradient g_v is reached at the wire surface any free ions are accelerated and produce other ions by collision with molecules, which are in turn accelerated. The ionic density is thus gradually increased by successive collision until at $0.301 \sqrt{r}$ cm. from the wire surface, where $g_0 = 31$, ionic saturation is reached, or corona starts. The distance $0.301 \sqrt{r}$ cm. is of course many times greater than the mean free path of the ion and many collisions must take place in this distance. Thus corona cannot form when a gradient of g_0 is reached at the surface of the wire, as at any distance from the surface the gradient is less than g_0.

The gradient at the surface must, therefore, be increased to g_v so that the gradient a finite distance away from the surface ($0.301 \sqrt{r}$ cm.) is g_0. This amounts to the same thing as saying that energy is necessary to start corona, as explained above.

The complete expression for g_v at different air densities is

$$g_v = g_0 \, \delta \left(1 + \frac{0.301}{\sqrt{\delta \, r}}\right) \tag{11}$$

This means that g_0, the strength of air, varies directly with δ. g_v, however, cannot vary directly with δ because, with the greater mean free path of the ion at lower air densities, a greater "accelerating", or energy, distance is necessary. In the equation $a = 0.301 \sqrt{r / \delta}$, that is, a increases with decreasing δ.

When the conductors are placed so close together that the free accelerating, or energy storage, distance is interfered with, the gradient g_v must be increased in order that ionic density may be reached in this limited distance. This is shown experimentally by sphere-gap tests.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

AN OSCILLOGRAPH STUDY OF CORONA

BY EDWARD BENNETT

Introduction

In the investigations which have heretofore appeared, dealing with the formation of corona around high-tension wires, the effect of the corona, or the partial breakdown of the air, on the charging current of the wires has not been determined by direct experimental methods. Oscillograms of the charging current of a conductor surrounded by corona not only afford a check on conclusions arrived at by independent methods of observation, but also throw additional light on the nature of the failure of the air around the conductor.

Three methods of using the oscillograph to determine the wave form of the charging current of a wire present themselves.

1. The oscillograph may be connected between the wire and the high-tension transformer which charges the wire.

2. The wire may be surrounded by a metal cylinder insulated from earth, and the displacement from the wire may be collected by this cylinder and sent to earth through the oscillograph as shown in Fig. 1.

3. The wire may be surrounded by an insulated metal cylinder as in the second method, but in this case the wire is connected to earth through the oscillograph, while the metal cylinder is maintained at the high potential.

The first method involves either:

a. The use of a current transformer with insulation between primary and secondary sufficient to withstand the potential between wire and earth and with the primary supplied by the charging current of at least several thousand feet of wire; or

b. The connection of the vibrator of the oscillograph directly in the high-tension line, and therefore the insulating of the entire oscillograph from earth. Neither of these alternatives is very satisfactory.

The third method is very similar to, and has most of the advantages of the second method, which is discussed at length hereafter. The third method is, however, not quite as convenient to use in crowded quarters as is the second.

Second Method. In collecting the charging current of the wire by a metal cylinder, as in the second method, it is to be noted that an oscillograph of the type used requires a current of from 0.05 to 0.08 peak amperes per centimeter deflection of the spot of light. The charging current of a wire 0.5 cm. in diameter at the voltage at which corona is visible is only 0.054 r.m.s. amperes per 1000 ft. (300 m.) at a frequency of 60 cycles. Therefore if the charging current of the wire is passed directly through the vibrator of the oscillograph, it will require at least 400 ft. (120 m.) of wire and enclosing cylinder to furnish enough current for satisfactory deflections. If, however, as shown in Fig. 2, a current transformer with a primary to secondary current ratio of 1 to 100 be interposed between the collecting cylinder and the vibrator of the oscillograph, satisfactory oscillograms of the charging current may be obtained with a length of wire and cylinder of only 10 ft. (3 m.). With this arrangement the conditions surrounding the wire may be easily varied and controlled. For example, the wire may be readily cleaned or polished, or the cylinder may be closed at both ends and partially exhausted. The oscillograms herein contained were obtained by the use of a collecting cylinder[1] and current transformer as outlined above.

This paper contains:

a. A description of this method and the apparatus used for obtaining oscillograms showing the form of the charging current of a 10-ft. (3-m.) length of wire at potentials below and above the corona voltage.

b. A series of oscillograms taken with the apparatus under varying air pressures and varying voltages on different conductors. These oscillograms show the marked asymmetry in the current after corona forms, the relation between power loss and im-

1. Much of the apparatus used in this work has been prepared by G. B. Blake, C. R. Higson and B. E. Miller in preliminary work along this line. In the experimental work great assistance has been rendered by B. E. Miller and L. E. A. Kelso.

pressed voltage, the start of corona after switching, the voltage at which ionization sets in, the marked difference in the results at high and low air pressures, etc.

II—Method and Apparatus

To obtain oscillograms of the charging current of a short length of wire, the circuits and apparatus represented in Fig. 2

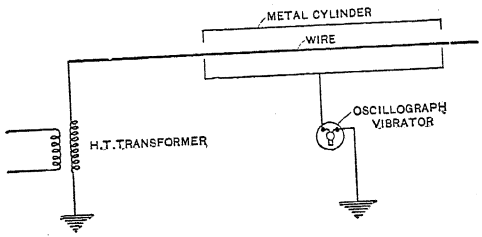


Fig. 1—Method of Obtaining Oscillograms of the Charging Current of a Wire

were used. In this figure, W is the wire whose charging current oscillogram is desired. This wire is stretched along the axis of the metal cylinder C and is held taut by the spring S. Two different cylinders were used at different times during the tests: an 8-in. iron pipe 20.6 cm. in diameter by 518 cm. long, and a cylinder of galvanized iron wire mesh. The galvanized mesh

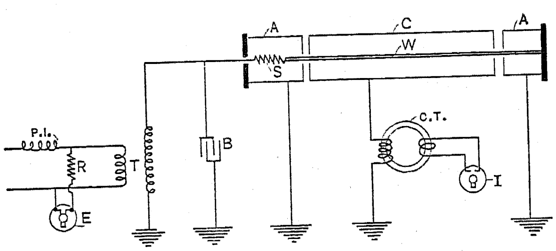


Fig. 2—Connections for Oscillograms of the Charging Current of a Wire

wire was 0.112 cm. in diameter, the mesh was 1.27 cm. square; the diameter of the mesh cylinder was 36.8 cm. and the length 311 cm. Grounded end shields A, 60 cm. long, were used at each end of the mesh cylinder. No shields were used with the iron pipe.

The wire W was connected to one terminal of the high-tension

winding of a 50-kv., 20-kw. transformer *T*, the other terminal of which was grounded. The voltage impressed on the primary was regulated by an induction regulator. *B* is a bank of Leyden jars so adjusted with respect to the air-core inductance *P.I.* inserted in the primary that the circuit offers a much higher impedance to any harmonics in the generator voltage than to the fundamental. This serves to sift out all harmonics in the generator wave form and to impress a pure sine voltage between wire and ground. The potential across the primary of the transformer is recorded by the oscillograph vibrator *E*.

The charging current of the wire *W*, in other words the current from the wire to the cylinder, is sent to ground through the primary of a current transformer *C.T.* the secondary of which is connected to the oscillograph vibrator *I* which records the current wave form. The current transformer is necessary because the current from wire to cylinder is of the order of half a milliampere while the vibrator *I* requires 50 milliamperes for a satisfactory deflection.

Frequency. All oscillograms and measurements were obtained at a frequency of 60 cycles per second.

Current Transformer. The current transformer is arranged for ratios of transformation of approximately 100, 200 and 600. At 60 cycles with the 100 to 1 connection, the ratio of the secondary to primary current is 98.9 to 1 and the secondary current leads the primary current by 1.3 degrees. With the 200 to 1 connection the ratio of secondary to primary current is 194.6 to 1 and the secondary leads the primary by 3 degrees. The constants of the transformer for all harmonics as high as the 15th are as good as the above constants.

The resistance of the transformer and vibrator reduced to the primary is 19850 ohms, and the 60-cycle leakage reactance is 4800 ohms. The vibrator *I* used in the secondary of the current transformer is a modified vibrator having only one half the length of silver of the standard vibrator and a resistance of 0.6 ohms.

To show the faithfulness with which harmonics are reproduced in the secondary of the current transformer, oscillogram 194 (Fig. 14) is here reproduced. This oscillogram was obtained by using the Fig. 2 connection with the following modifications. The inductance *P.I.* was omitted and the charging current of the condenser *B* was passed directly through the third vibrator *P* of the oscillograph by connecting the vibrator in the circuit between *B* and ground.

The curve P was traced by the vibrator P and the curve S by the vibrator in the secondary of the current transformer. Below the corona voltage, the charging current of the condenser B and of the wire in the cylinder C should have the same wave forms; any appreciable errors introduced by the current transformer should cause an appreciable difference in the shapes of the current wave forms P and S. An inspection of the oscillogram shows that harmonics in the primary of the current transformer are accurately reproduced in the secondary.

Sifting Out the Harmonics in the Generator Voltage. The voltage of the generator from which power was obtained contains high harmonics of such small amplitude that they can just be detected in oscillograms of the voltage wave form. In the charging current of the wire, however, these harmonics are amplified to such an extent that they entirely mask the effect of the first stages of corona formation. The record of the oscillograms is far more intelligible if the harmonics are all sifted out, so that the effect of the corona is superimposed on a pure sine curve. This was accomplished as previously stated by proportioning the reactances of the bank of Leyden jars B and the air-core inductance $P.I.$ in the transformer primary so that the harmonics would all be consumed in the inductance, $P.I.$ Fig. 3 is a schematic diagram showing the constants of the circuit consisting of the high-tension transformer with the condensers and inductance for sifting out the harmonics. All resistances and reactances are reduced to the high tension circuit and are expressed in megohms. Oscillograms 177 to 181 are intended to contrast the results obtained with and without sifting out the harmonics. These oscillograms were all obtained with the Fig. 2 connections using a polished copper wire 0.227 centimeters in diameter and an iron pipe 20.6 centimeters in diameter. Corona was visible around the wire at 18 kv. Oscillograms 180 and 181 were taken without the condenser B and the inductance $P.I.$,

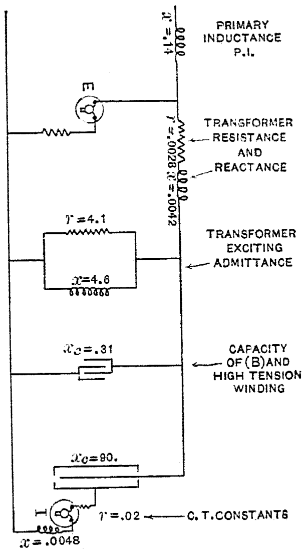


FIG. 3—CONSTANTS OF THE CIRCUITS

Resistances and reactances are expressed in megohms, all reduced to the high-tension circuit: frequency 60 cycles.

below and above the corona voltage respectively. It is impossible to detect the harmonics in the e.m.f. wave form, but they render the current wave form so jagged that the details brought out in oscillogram 178 would be lost. Oscillograms 177 to 179 were obtained with the harmonics sifted out.

High-Tension Transformer-Phase Relations of Primary and Secondary Voltages. Since the voltage recorded on all oscillograms is the voltage impressed on the primary of the step-up transformer it is necessary to determine the phase relation between the primary and the high-tension voltage. The high-tension transformer is a 20-kw. 50-kv. transformer which throughout the tests was connected for a ratio of transformation of 250 to 1. The high-tension full load current of this transformer is 0.4 amperes. The charging current of the condenser B and the

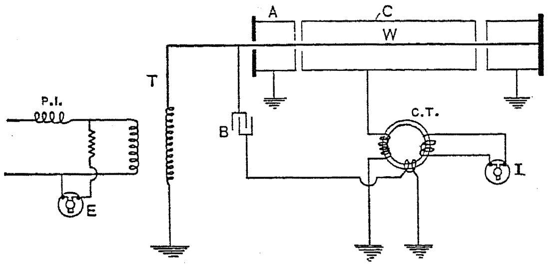


FIG. 4—DIFFERENTIAL CONNECTIONS FOR ELIMINATING CHARGING CURRENT

wire W is the only current delivered by the transformer. The charging current of the wire is about 1/200 of the charging current of the condenser or is negligible in comparison. The capacity of the condenser B was varied within narrow limits during the tests but was generally kept at 7.3×10^{-9} farads. At 60 cycles and 50 kv. the charging current of this capacity is 0.14 amperes or only 35 per cent of the full load current of the transformer. Since at full load the resistance and the reactance drops of the transformer are 2.3 per cent and 3.5 per cent respectively, it follows that the high-tension voltage leads the primary or recorded voltage by 0.5 degrees and is 1.2 per cent higher than the no-load voltage.

Since the current in the secondary of the current transformer, —and through the current vibrator—leads the current in the primary of the transformer—the true charging current,— by

1.3 deg., it follows that the phase relation of current to voltage as recorded on the oscillograms is correct to within one degree. To get the correct relations the voltage wave should be advanced by 0.8 degree.

Differential Connection for Eliminating the Charging Current. At voltages slightly higher than the voltage at which corona forms around a wire, the effect of ionization on the current wave form can be shown to better advantage by neutralizing the charging current of the wire in the manner shown in Fig. 4.

The connections of Fig. 4 differ from those of Fig. 2 in that the current transformer is connected for a ratio of 200 to 1 and the charging current of the condenser *B* is passed through one of the coils of the transformer, in the opposite direction to the current in the primary. The capacity of *B* is adjusted so that its charging current just balances and neutralizes the magnetomotive force of the charging current of the wire at voltages below the corona voltage. The current vibrator in the secondary of the transformer, as a result, traces a straight line at any voltage below the corona voltage. Above the corona voltage the charging current of the condenser *B* no longer balances the current between the wire and cylinder, and the current vibrator shows the current which is superimposed on the charging current as a result of the ionization around the wire.

III—Observations and Deductions

The oscillograms obtained with the circuits and apparatus above described are grouped and discussed in the following pages:

Oscillogram Notation. Explanation of Terms. The connections of the oscillograph were such that for all films the following relations apply:

A positive deflection (a deflection above the zero line) of the current vibrator indicates a current from the enclosing cylinder to the wire *W*, *i.e.*, the wire is cathode or negative to the cylinder.

A negative deflection of the current vibrator therefore indicates a current from wire to enclosing cylinder, *i.e.*, the wire is anode. The same conventions of course must hold for deflections of the potential vibrator. On some of the films these conventions have been indicated by the use of two concentric circles representing the wire and its enclosing cylinder, and appropriately marked + and −. Thus if the circles are placed above the zero line they indicate the polarities for positive deflections and the inner circle is marked − and the outer +. If the circles

are below the zero line they indicate the polarities for negative deflections and the inner circle is positive and the outer negative. On all oscillograms the current wave form is designated by i, the voltage wave by e.

Instant of Copious Ionization. Voltage at Copious Ionization. All oscillograms taken at a voltage high enough to cause the formation of corona are characterized by a sudden increase in the current similar to the increase which is shown at the instants t_1 and t_2 in Fig. 5. In the discussion of the oscillograms this instant of time, at which the current suddenly " shoots up," is designated as the "Instant of *Copious* Ionization." In specifying the instant of copious ionization, it is convenient to locate it with reference to the succeeding voltage peak; thus, the instant of copious ionization occurs n degrees ahead of the voltage peak.

The instantaneous value of the voltage between wire and cylinder at the instant of copious ionization is designated as the Voltage at Copious Ionization. " Instant of Ionization " conveys the impression that no ionization occurs during the part of the cycle immediately preceding the " Instant of Ionization." This notion may be very misleading; it is avoided by prefixing copious to ionization.

Hypothetical Gradient. If the air between the wire and the concentric cylinder used in these experiments acts as a pure dielectric, permitting of an elastic displacement only, the electric intensity or potential gradient g at any instant at a point at a distance x from the axis of the cylinders is

$$g = \frac{e}{\log \frac{b}{a}} \frac{1}{x} \tag{1}$$

in which e is the difference of potential between the cylinders at the instant.

b is the radius of the outer cylinder.

a is the radius of the wire.

This expression for the gradient does not apply if there is an accumulation of charge, that is, an excess of positive or negative ions in any region. The hypothesis under which the gradient is computed in equation (**1**), namely, that the gas permits of elastic displacement only, is untenable at potentials which cause corona around the inner cylinder. It may also be untenable at lower potentials. To avoid the mental confusion which may arise from

the use of an untenable hypothesis, a gradient computed by the use of equation (**1**) is called an "Hypothetical Gradient." The computed hypothetical gradient is a very useful notion only as long as its hypothetical nature is not lost sight of.

By the hypothetical surface gradient (*h.s.g.*) is meant the hypothetical gradient at the surface of the inner cylinder

$$h.\ s.\ g. = \frac{e}{a \log \frac{b}{a}} \tag{2}$$

General Experimental Observations. Oscillograms 183 to 186 and 187 to 191 are intended to illustrate the observations described below. These oscillograms were obtained with a polished steel wire 0.059 cm. in diameter in the 8-in. (20.6 cm.) iron pipe, at an air pressure of 74 cm. of mercury. The first four oscillograms were obtained with the Fig. 2 connections and the last four with the charging current of the wire neutralized by the differential connection of Fig. 4. Corona forms around this wire at 10.45 r.m.s. kv. between wire and cylinder. The hypothetical gradient in kv. per cm. at the surface of this wire equals 5.80 times the voltage between wire and cylinder.

If, as the voltage impressed between the polished wire W and cylinder of Fig. 2 is slowly increased, the charging current of the wire is observed on the tracing table of the oscillograph, the following relations are noted:

1. As the voltage is slowly increased, simultaneously,—that is, at the same voltage within several tenths of one per cent,—with the appearance of the bluish haze around the wire and the occurrence of the hissing sound, a small hump or peak appears on the current wave under each voltage peak. The voltage at which this occurs has been variously designated as the "visual critical voltage" or "corona voltage" for the particular wire and cylinder. The ordinates of the hump which is superimposed on the sine charging current show the instantaneous values of the increase in current resulting from ionization after the corona voltage is exceeded. Oscillograms 183, 184 and 188 show the appearance of the oscillograms at voltages slightly higher than the corona voltage.

2. When observing the current wave form on the tracing table of the oscillograph, the hump on the current wave form can generally be detected under the negative voltage peak at a volt-

age a few tenths of a per cent below the voltage at which the positive hump is detected. That is, the hump is first detected during the half cycle in which the wire is anode and the cylinder cathode. This condition, however, has never been recorded on any of the photographic records. It is possible that the negative hump is *detected* before the positive, not because ionization occurs at a lower voltage when the wire is anode than when it is cathode, but because the negative hump at its first appearance is short and peaked and is consequently easier to detect than the positive which is broad and low. This difference between the positive and negative humps at voltages slightly higher than the corona voltage is shown on oscillogram 183.

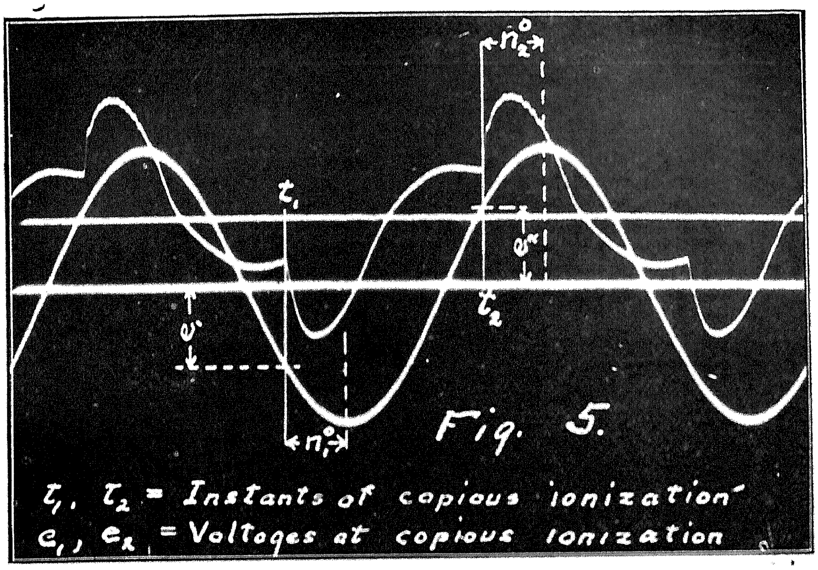
At pressures below 20 cm. of mercury, the positive hump is always observed before the negative appears; that is, copious ionization sets in at a lower voltage when the wire is negative than when it is positive.

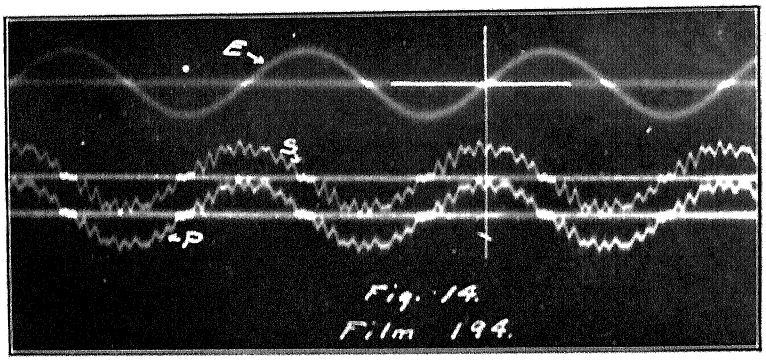
3. On slowly lowering the voltage, the hump does not disappear from the current wave, nor does the hissing cease, until the voltage is from one to three per cent lower than the value at which they are first observed with increasing voltage. This would indicate that the ions persisting from any preceding half cycle facilitate the start of copious ionization in the succeeding half cycle.

4. At impressed voltages below the corona voltage the charging current of the wire is a sine current 90 deg. in advance of the voltage. That is, any loss resulting from ions present or ions formed below the corona voltage, is so small that it cannot be detected by the oscillograph.

5. The asymmetry in the current wave form to be noted in the series of oscillograms from 183 to 191 is not peculiar to the particular wire used, but is characteristic of all wires tried. The oscillation in the current occurs when the wire is cathode to the cylinder; only slight traces of an oscillation can be detected in the current when the wire is anode. The oscillation is more marked for finely polished wires than for weathered wires. This oscillation is later shown to be a result of the rapidity and suddenness with which the air in the vicinity of the wire loses its insulating properties.

6. It will be noted that the increase in current resulting from ionization is not a smooth or gradual increase with the increasing voltage during the cycle; at a certain voltage the current "shoots" up very rapidly. The instant at which this occurs is designated


n_2°
t_1
e_2
t_2
e_1
n_1°
Fig. 5.
t_1, t_2 = Instants of copious ionization
e_1, e_2 = Voltages at copious ionization


E
S
P
Fig. 14.
Film 194.

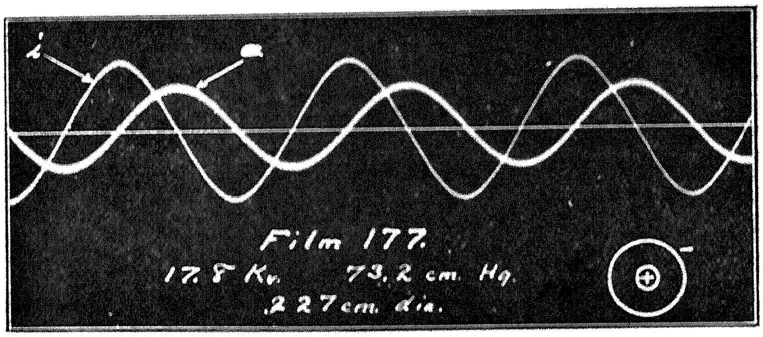
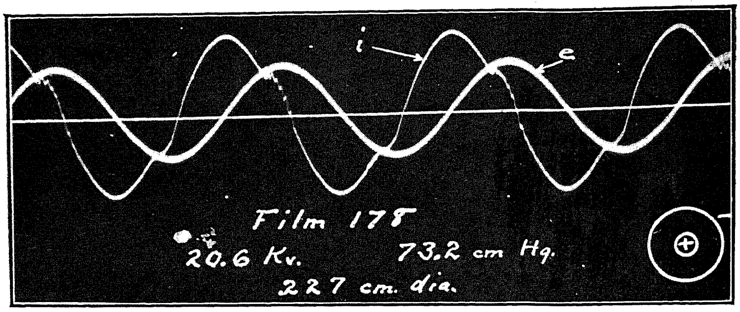
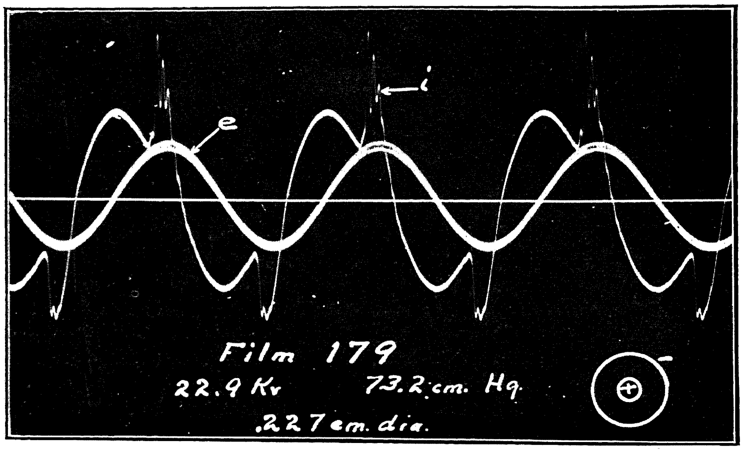
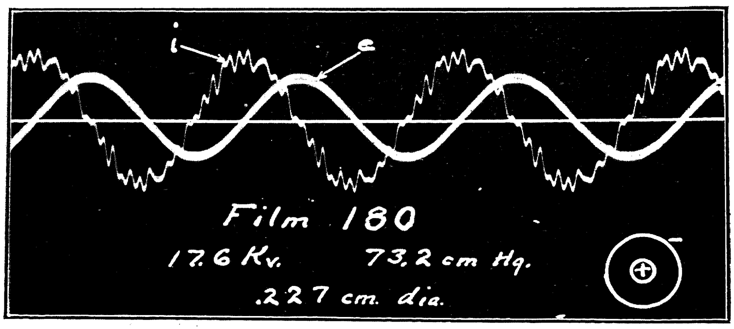

i
e
Film 177.
17.8 Kv. 73.2 cm. Hg.
.227 cm. dia.
+
−

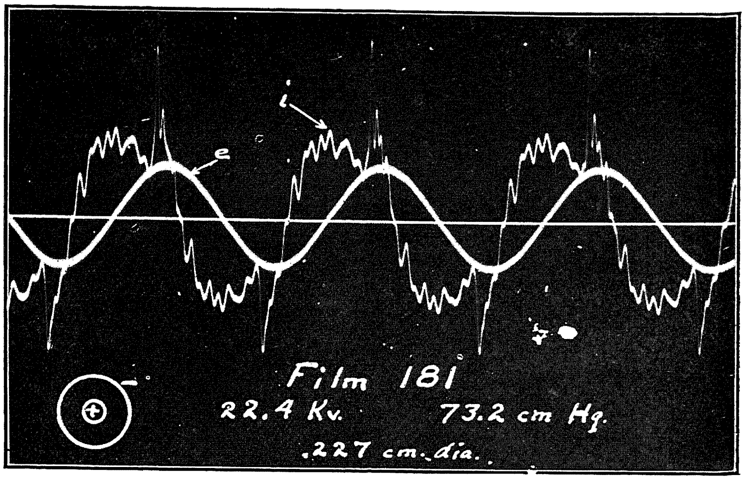
PLATE XLV
A. I. E. E.
VOL. XXXII, 1913

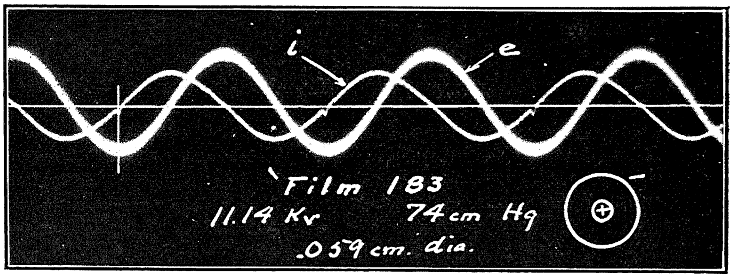


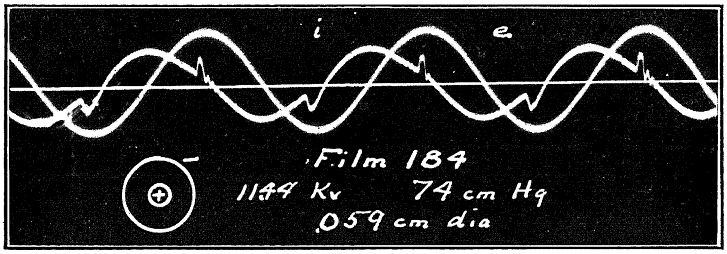


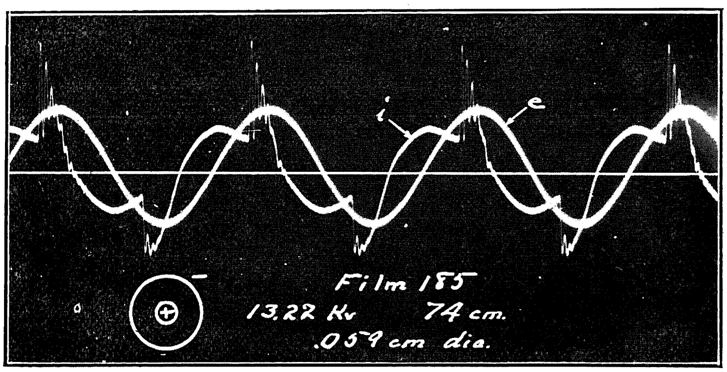


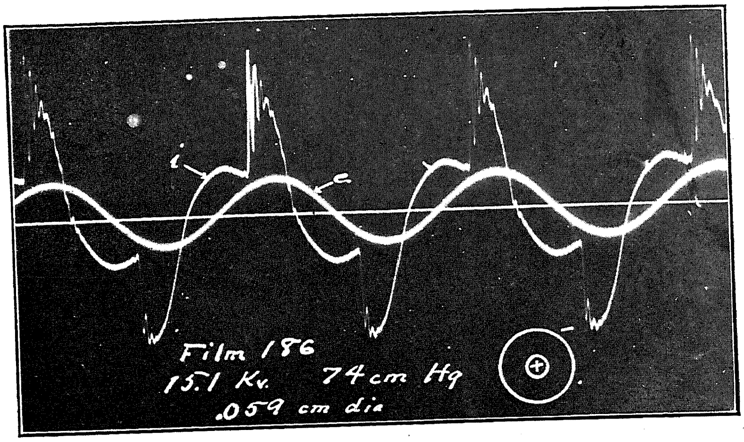
[BENNETT]

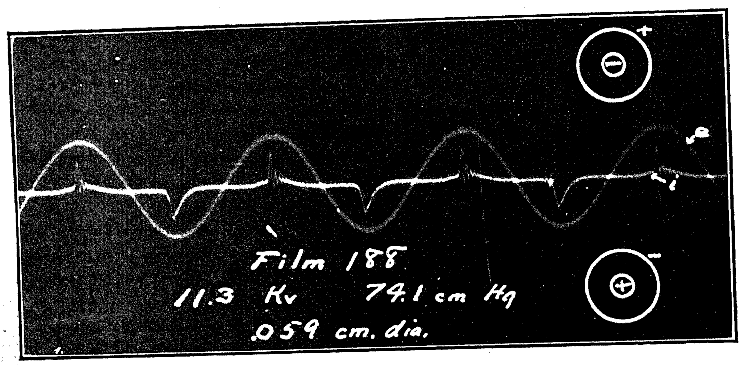

i
e
Film 181
22.4 Kv.
73.2 cm Hg.
.227 cm. dia.

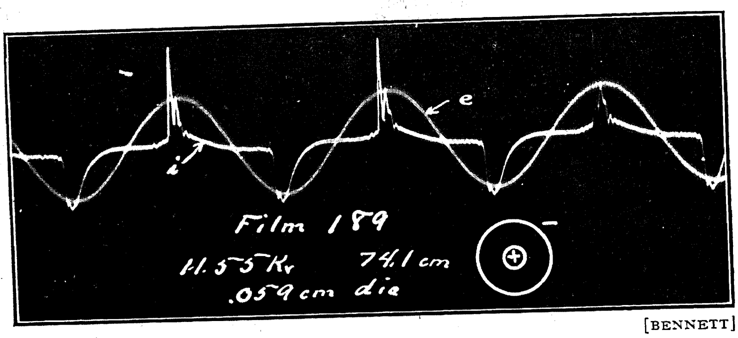

i
e
Film 183
11.14 Kv
74 cm Hg
.059 cm. dia.


i
e
Film 184
1144 Kv
74 cm Hg
.059 cm dia


i
e
Film 185
13.22 Kv
74 cm.
.059 cm dia.


i
e
Film 186
15.1 Kv. 74 cm Hg
.059 cm dia


e
i
Film 188
11.3 Kv 74.1 cm Hg
.059 cm. dia.


e
i
Film 189
11.55 Kv 74.1 cm
.059 cm dia

[BENNETT]

as the "instant of copious ionization." An inspection of the oscillograms obtained with the differential connection indicates that some current flows during each half cycle before copious ionization sets in.

The Oscillation in the Current. The interpretation of the oscillation to be observed in the current wave forms was for some time quite puzzling. The oscillation unquestionably indicates that there is a difference in the nature of the failure of the air, depending upon the direction of movement of the ions. The marked oscillation is always obtained when the wire is cathode, that is, when the negative ions move from a field of high to a field of low intensity and the positive ions in the reverse direction.

Both inductance and capacity are required for the oscillations shown on the oscillograms. Since the element of inductance in the part of the circuit between the wire and the cylinder is negligible, it did not seem possible that the oscillation could be in the movements of the ions in the ionized regions surrounding the wire. It was finally suspected that the oscillation resulted from the suddenness of the breakdown around the wire; and that the oscillatory circuit consisted of the current transformer and the capacity of the cylinder C to earth. The inductance of the circuit would be due to the leakage flux of the current transformer, which, in the paper previously referred to, is shown to be 12.7 henrys. The capacity to earth of the 10-ft. (3-m.) wire mesh cylinder and its connections was estimated at 2.3×10^{-10} farads. The natural frequency of oscillation of such a circuit is 2940 cycles per second; the critical resistance required to render the circuit non-oscillatory is 470,000 ohms. The frequency of oscillation found by scaling the films is 2720 cycles per second, which is 8 per cent lower than the computed frequency,—a fairly satisfactory agreement in view of the difficulty of estimating the capacity.

To determine beyond question the part of the circuit which takes part in the oscillation, the resistance, inductance, and capacity of the suspected oscillatory circuit were varied and the corresponding frequencies of oscillation were recorded on a series of oscillograms. These oscillograms were all obtained with a polished phosphor bronze wire 0.102 cm. in diameter in the wire mesh cylinder of 36.8 cm. diameter. The corona voltage for this wire is 14.7 r.m.s. kv. with increasing voltage. The oscillograms were all taken at approximately 15.2 r.m.s. kv.

Oscillogram 262 records the frequency of oscillation with the

Fig. 2 connections. As stated above, the recorded frequency is 2720 cycles per second, or 8 per cent lower than the frequency calculated from the roughly estimated constants. Contrast the amplitude of oscillation on oscillogram 262 with that on 259. Oscillograms 262 was obtained with the polished wire and 259 with the same wire before polishing. The amplitude of oscillation is much greater with the polished wire.

Fig. 6 shows the manner of connecting in additional inductance and capacity for the purpose of varying the constants of the oscillatory circuit. The additional resistance or the inductance was connected in series with the current transformer, between transformer and cylinder at *D*. The additional capacity, a 2.04×10^{-9} farad Leyden jar, *F*, was connected in parallel with the capacity of the wire mesh cylinder to earth.

Oscillogram 256 was obtained with an inductance of 24.6

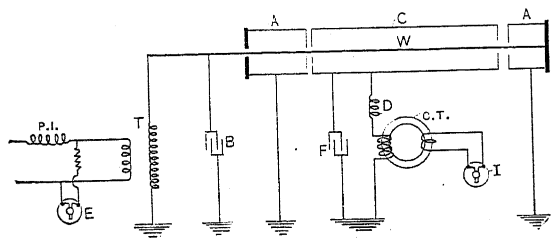


FIG. 6

henrys connected in at *D* and with the condenser *F* disconnected. The computed frequency is 1685 cycles per second and the frequency recorded on the film is 1640 cycles,—a difference of 3 per cent. Note that for this slowed down circuit, the breakdown of the air when the wire is anode is rapid enough to set up a slight oscillation.

Oscillogram 258 was now taken with the 24.6-henry inductance at *D* and the 2.04×10^{-9} farad condenser at *F*. The computed frequency is 545 cycles and the frequency recorded on the films 540 cycles per second,—a difference of one per cent.

Finally oscillogram 264 was taken without the condenser *F* or the inductance, but with a 0.94-megohm water tube resistance at *D*. Although this is twice the critical resistance of the oscillatory circuit of Fig. 2, there are still ripples to be detected in the positive hump; with this resistance the negative hump is perfectly smooth.

These tests confirm the conclusion that the oscillation results from the suddenness of the breakdown of the air around the wire and that the oscillatory circuit consists of the current transformer and the capacity of the cylinder C to earth. The inductance of the current transformer, by causing the overshooting, has served to bring out in a very striking manner the explosive suddenness with which the air around the wire loses its insulating properties when the wire is the cathode.

Relation between Watt Expenditure and the Impressed Voltage. The series of oscillograms from 261 to 269 was taken to determine the relation between the watt expenditure in the corona and the voltage impressed between wire and cylinder. These films were all obtained with the 0.102-cm. polished phosphor bronze wire in the mesh cylinder of 36.8 cm. diameter. Fig. 2 connections were used, modified, however, by inserting the 0.94-megohm resistance at D between the cylinder C and the current transformer in order to damp out the oscillation. The constant of the current vibrator was the same throughout this series. A critical examination of these films discloses the following relations:

1. With increasing voltages impressed between wire and cylinder, copious ionization occurs earlier and earlier in each half cycle. The relation between the impressed voltage and the angular interval between the instant of copious ionization and the succeeding voltage peak is shown in Fig. 7.

2. With increasing impressed voltages, the instantaneous voltage at which copious ionization sets in becomes smaller and smaller. The relation between the impressed voltage and the instantaneous voltage at the instant of copious ionization is shown in Fig. 7. At the higher voltages the period of ionization extends over a greater portion of each half cycle than at the lower voltages and the production of ions ceases later in each half cycle. The lowering, with increasing impressed voltage, of the voltage at which copious ionization sets in, may result from the great number of ions remaining from the previous half cycle at the higher voltages. Note that the voltage at which copious ionization occurs is lower when the wire is cathode than when it is anode.

3. A close examination of these oscillograms, especially at the lower voltages, indicates a slight current flow, such as might be attributed to the movement of ions, previous to the instant of copious ionization. This is brought out more clearly in oscillograms, 271 and 272, taken on the same wire, but with the charg-

ing current of the wire neutralized by the differential connections of Fig. 4. The current is quite appreciable before the start of copious ionization.

4. On these same oscillograms, 271 and 272, it will be noted that the current reverses before the voltage. This may indicate a reverse movement of the separated positive and negative ions before the reversal of the hypothetical gradient calculated from the instantaneous impressed voltages.

5. A casual inspection of the oscillograms 271 and 272 shows

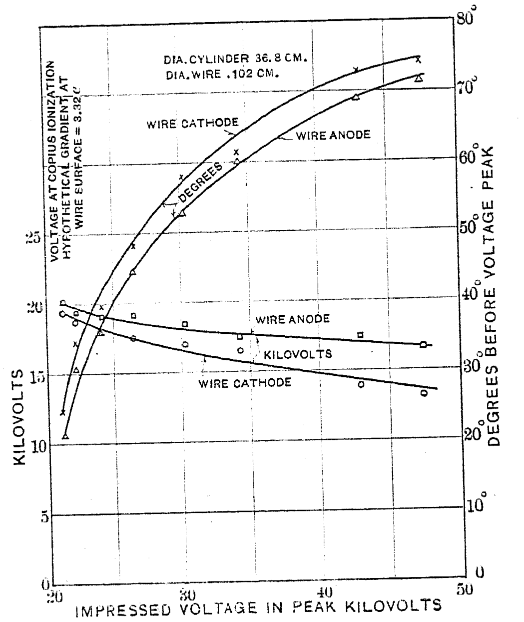
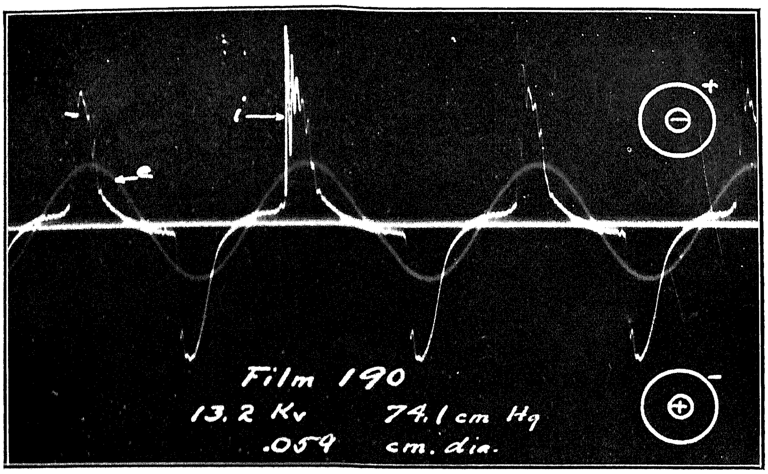
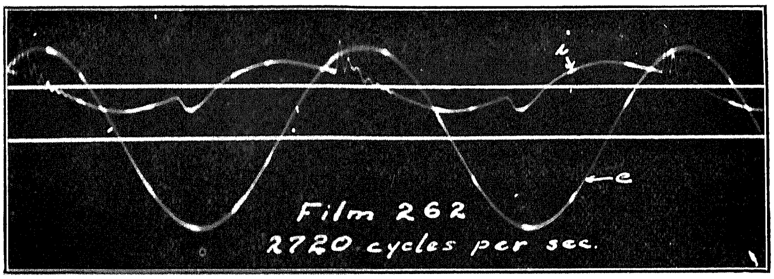


FIG. 7—RELATION BETWEEN IMPRESSED VOLTAGE AND (A) VOLTAGE AT COPIOUS IONIZATION (B) INSTANT OF COPIOUS IONIZATION

that at voltages slightly greater than the corona voltage the watt expenditure in the corona is greater during the negative half cycle—when the wire is anode—than during the positive half cycle. This is borne out by the calculations described in the next paragraph.

6. The watt expenditure between wire and cylinder was computed for the series of oscillograms 261 to 269 by placing each film over millimeter cross-section paper, reading off the corresponding values of voltage and current ordinates one millimeter apart,


i
e
Film 190
13.2 Kv 74.1 cm Hg
.059 cm. dia.


i
e
Film 262
2720 cycles per sec.

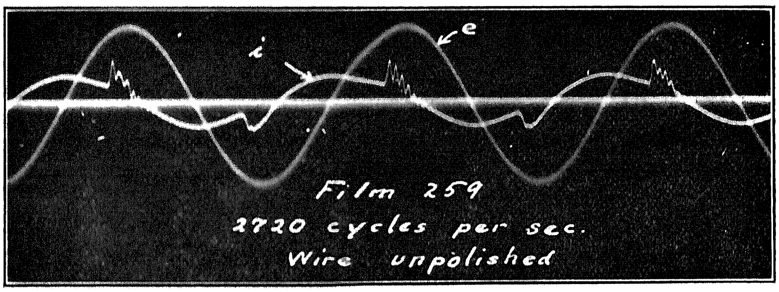
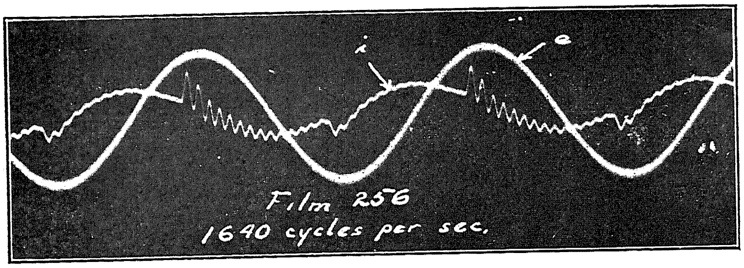
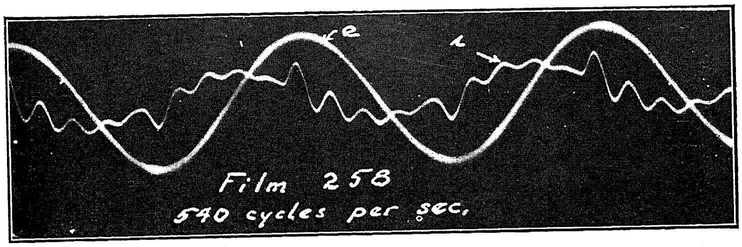
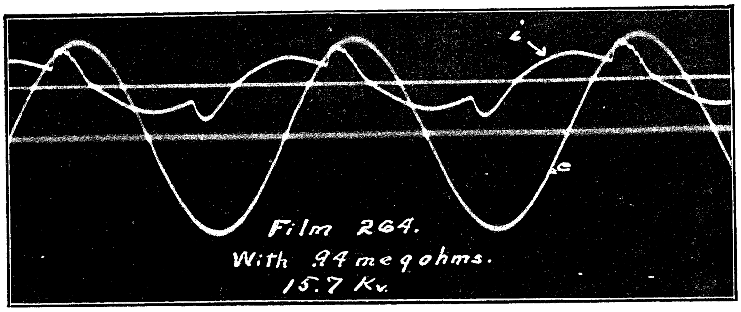
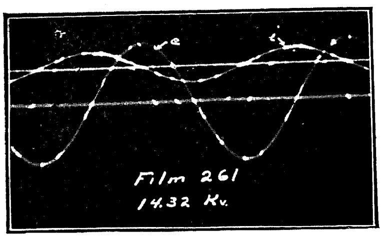

e
i
Film 259
2720 cycles per sec.
Wire unpolished

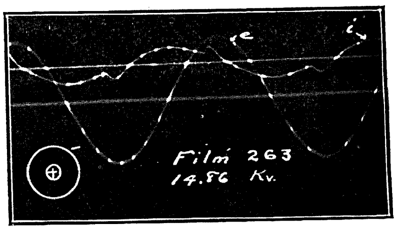
PLATE XLIX
A. I. E. E.
VOL. XXXII, 1913

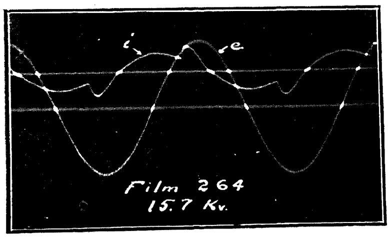


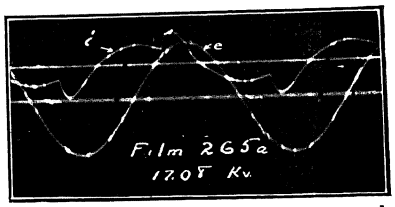




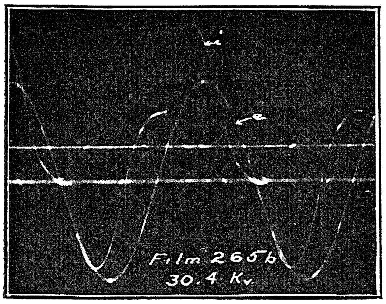


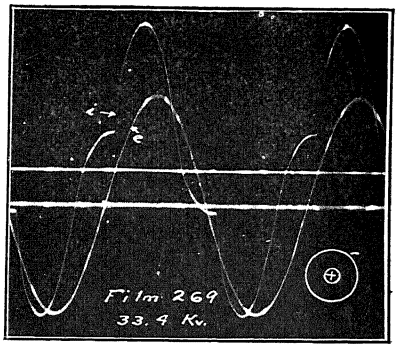


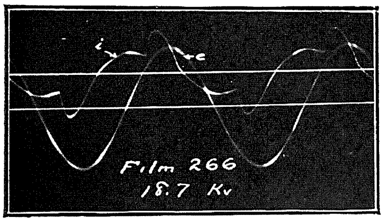


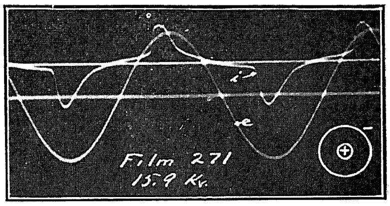


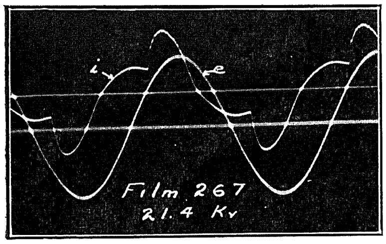
[BENNETT]

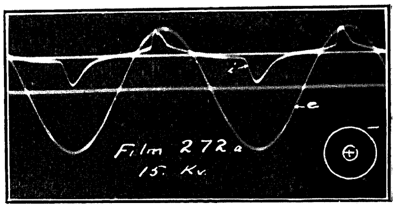

i
e
Film 265b
30.4 Kv.

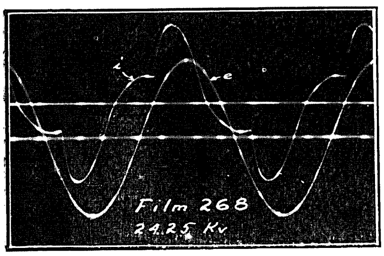

i
e
Film 269
33.4 Kv.

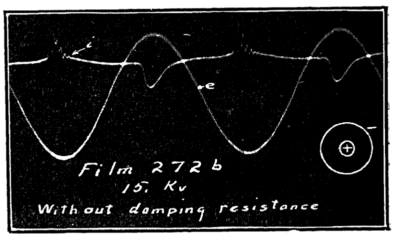

i
e
Film 266
18.7 Kv


i
e
Film 271
15.9 Kv.


i
e
Film 267
21.4 Kv


i
e
Film 272a
15. Kv.


i
e
Film 268
24.25 Kv


i
e
Film 272b
15. Kv
With out damping resistance

computing therefrom the power curve, and taking the sum of the products for the positive half cycle, the negative half cycle and for the entire cycle. The results are tabulated below in Table I and are plotted in Fig. 8.

TABLE I

Impressed Voltage and Corresponding Watt Loss between Concentric Cylinders.
Inner cylinder—polished phosphor bronze wire 0.102 cm. in diameter.
Outer cylinder—of wire mesh. 36.8 cm. in diameter by 311 cm. in length.

Oscillogram	Peak kilovolts	Power expenditure in watts		
		Positive half cycle	Negative half cycle	Entire cycle
261	20.25	−0.006	−0.015	−0.011
263	21.05	0.818	1.05	+0.934
264	22.2	1.815	1.915	1.86
265 a	24.15	2.76	2.89	2.825
266	26.45	4.46	4.79	4.625
267	30.25	8.60	8.76	8.68
268	34.35	13.81	14.33	14.07
265 b	43.0	30.85	30.65	30.75
269	47.50	42.4	42.30	42.35

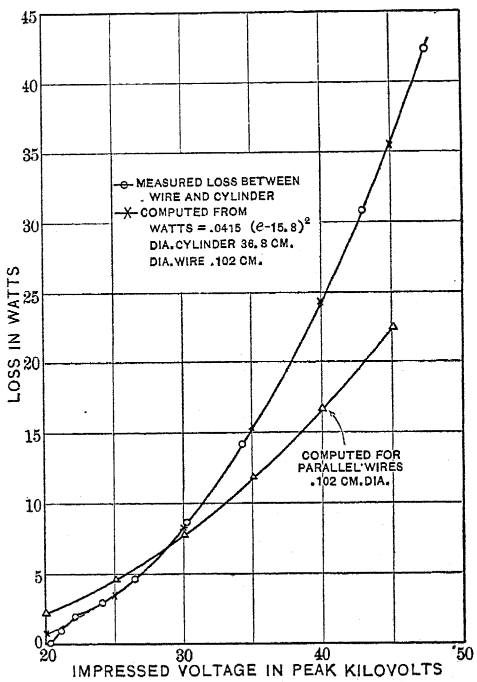


FIG. 8—RELATION BETWEEN IMPRESSED VOLTAGE AND POWER LOSS IN THE CORONA

At voltages slightly higher than the corona voltage, the loss is at least 20 per cent greater during the half cycle when the wire is anode than during the half cycle in which it is cathode.

This percentage difference becomes less with increasing voltage and is inappreciable at the higher voltages.

Peek[2] has shown that the loss P between the parallel wires is related to the voltage e between wire and neutral by an equation of the form

$$P = K\,(e - e_0)^2 \tag{3}$$

If the assumption is made that the equation of the loss-voltage curve plotted in Fig, 8 is of this form, and if the losses at 25 and 40 peak kv. are used to compute the values of the constants K and e_0, the following values are obtained:

$$K = 0.0415 \qquad e_0 = 15.8 \text{ peak kv.}$$

The resulting equation is

$$P = 0.0415\,(e - 15.8)^2 \tag{4}$$

where

P = loss in watts

e = peak kilowatts between wire and cylinder.

The points on Fig. 8 indicated thus (x) were computed from equation (**4**). The close agreement of these points with the experimentally determined losses indicates that equation (**4**) expresses the relation between loss and voltage very exactly except at voltages slightly higher than the corona voltage. At low voltages the actual loss is less than the loss computed from equation (**4**).

It is interesting to compare the constants of equation (**4**) for the loss between concentric cylinders with the constants of the equation given by Peek for the loss from a single conductor of two parallel conductors. Peek's equation is

$$P \text{ (in watts)} = 172\,\frac{l\,f}{\delta}\sqrt{\frac{r}{s}}\,(e - e_0)^2\,10^{-5} \tag{5}$$

in which e_0 is the peak value of the voltage to neutral, expressed in kilovolts which will produce a hypothetical gradient of 29.8 kilovolts at the surface of the conductors. Now the hypothetical gradient at the surface of a wire of radius r in a cylinder of radius b with a voltage e between wire and cylinders is equal to the hy-

2. *The Law of Corona and Dielectric Strength of Air*, by F. W. Peek, Jr., A. I. E. E. Transactions, Vol. XXX, 1911, and Vol. XXXI, 1912.

pothetical gradient at the surface of the same wire if used as one of the parallel wires, provided the voltage from wires to neutral is equal to the voltage e and the distance s between the centers of the wires is equal to the radius b of the outer cylinder. As the basis on which to compare the loss from one wire of a pair of parallel wires with the loss between the same wire and a concentric cylinder let these conditions be imposed: (1) the voltage from the wire to neutral in the first case is to equal the voltage between wire and cylinder in the second case, (2) the distance between the centers of the parallel conductors is to equal the radius of the outer cylinder, thus making the hypothetical surface gradients equal in the two cases. Substituting in equation (**5**)

$l = 3.11$ meters.
$f = 60$ cycles
$\delta = 0.984$ for a temperature of 21 deg. cent. at a pressure of 73.8 cm.
$r = 0.051$ cm.
$s = 18.4$ cm.
$e_0 = 29.8\, r\, \delta \log s/r = 8.85$ peak kilovolts

it becomes

$$P = 0.0172\,(e - 8.85)^2 \qquad (6)$$

in which $e =$ peak kilovolts to neutral.

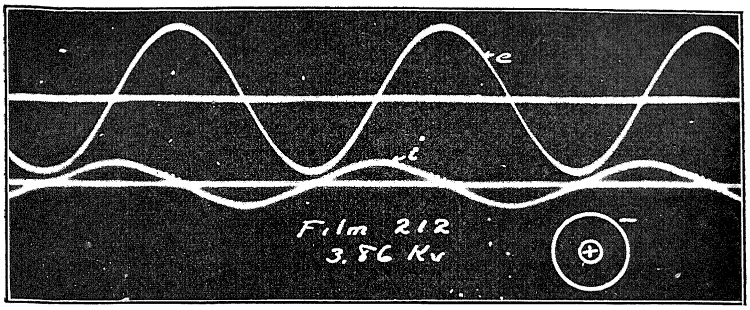
The loss-voltage curve for parallel conductors as computed from equation (**6**) is also plotted in Fig. 8. The great difference in the values of e_0 for the two cases,—15.8 peak kv. for concentric cylinders, and only 8.85 peak kv. for parallel wires,—was unexpected. No general conclusions can be drawn, however, on the basis of measurements on a single size of wire.

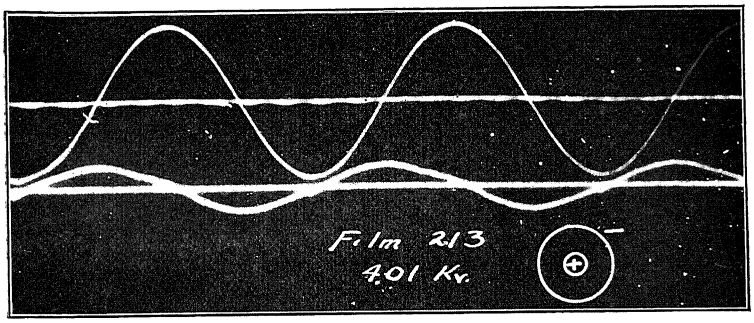
Observations at Air Pressure below Atmospheric. For the study of corona formation at pressures below atmospheric, the enclosing cylinder C, used with the Fig. 2 connections, was the 8-in. (20.6 cm.) iron pipe, provided with air-tight wooden bulkheads. The air was partially exhausted from this pipe and the wave form of the current between wire and pipe observed on the tracing table of the oscillograph at all pressures from atmospheric down to 0.13 cm. of mercury.

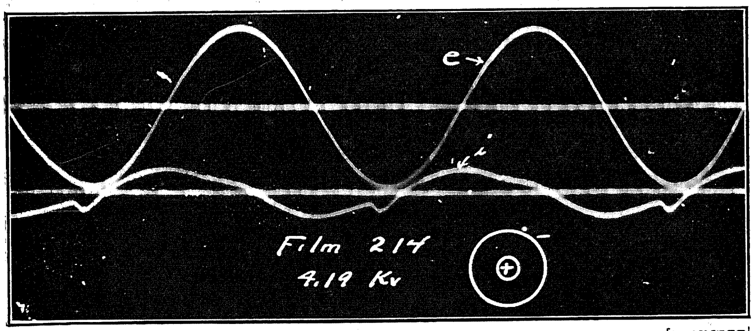
If, with the 0.102-cm. phosphor bronze wire in the pipe, the air pressure in the pipe is maintained constant at a given value, and the impressed voltage between wire and pipe is slowly increased, the following changes in the current wave form are noted with the increasing voltage:

1. At pressures between 76 cm. and 19 cm. of mercury:
   (a) The negative hump is detected first.
   (b) At a voltage about 0.2 per cent higher the positive hump is detected.
   (c) At a voltage still higher by 2 to 4 per cent, both humps "shoot up" in height very rapidly with slight increases in voltage.
   (d) At low voltages the negative hump is higher and of greater area than the positive but with increasing voltage the height of the positive hump overtakes and may slightly exceed the height of the negative.
   (e) The positive hump is markedly oscillatory—the negative is smooth.
   (f) The oscillograms do not differ materially in character from those at atmospheric pressures.
2. At pressures between 15 cm. and 3 cm. of mercury:
   (a) The positive hump is detected first.
   (b) Slight traces of oscillation are still to be detected in the positive hump.
   (c) The humps gradually get larger with increasing voltages, but do not at any time give the impression of "shooting up" rapidly with slight increases in the impressed voltage.
   (d) At low voltages the height of the negative hump exceeds the positive, but at higher voltages the height of the positive greatly exceeds that of the negative.
   (e) The series of oscillograms from 212 to 219 show the characteristic changes with increasing voltages for this range of pressures. These oscillograms were taken at a pressure of 13.7 cm. of mercury, with the Fig. 2 connections, and without using the 0.94-megohm resistance.

3. At pressures between 2.5 cm. and 0.13 cm. of mercury: For this range of pressures the changes in the current wave form with increasing impressed voltage can best be described by reference to oscillograms 221 to 223 and 232, which show the characteristic appearance of the current wave form for this range of pressures. These oscillograms were all obtained with the Fig. 2 connections, modified, however, by connecting the potential vibrator E and its series resistance directly across the high-tension side of the step-up transformers. The voltage at







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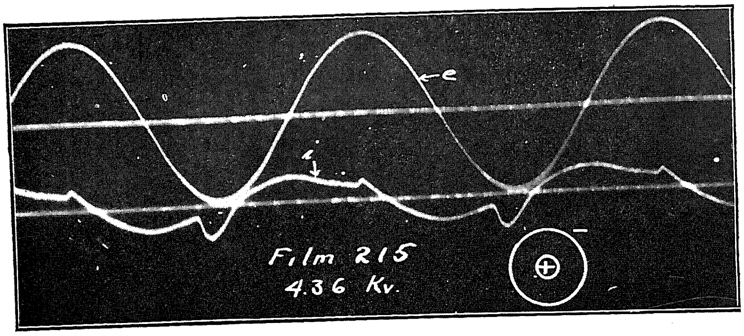

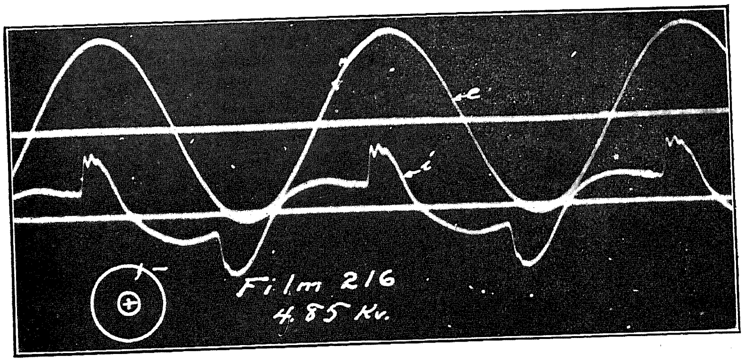

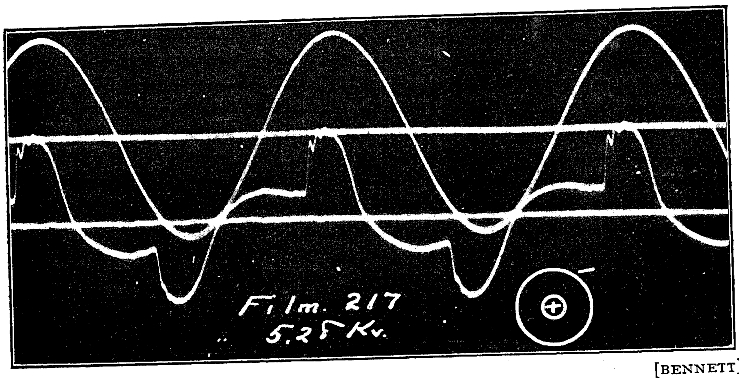

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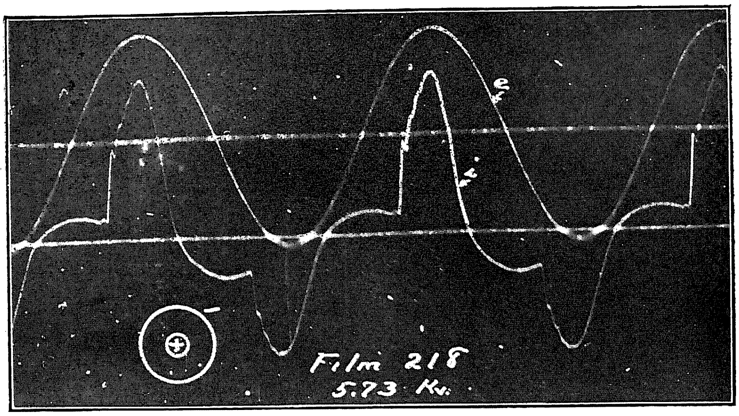
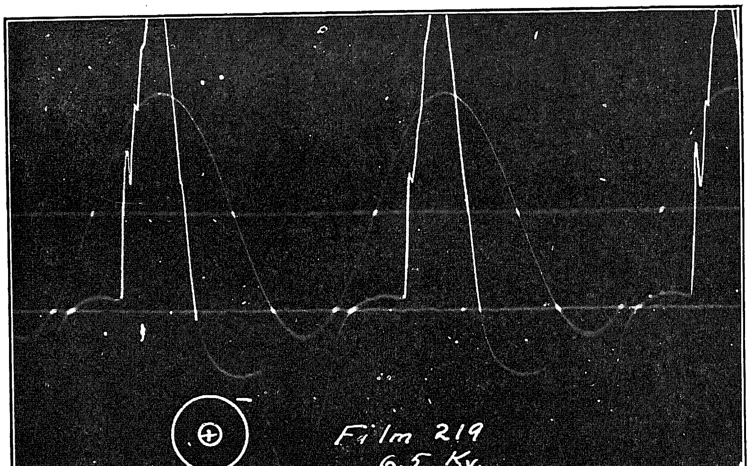
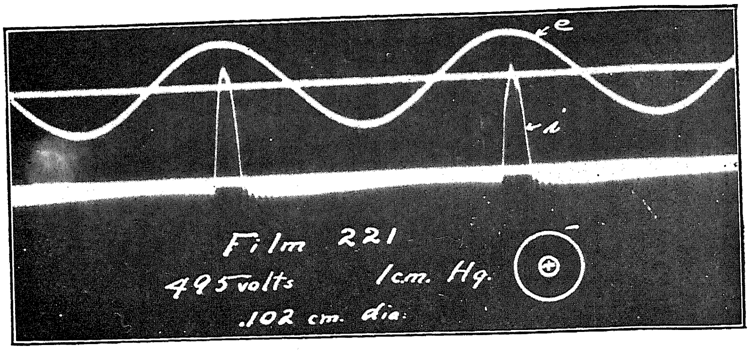
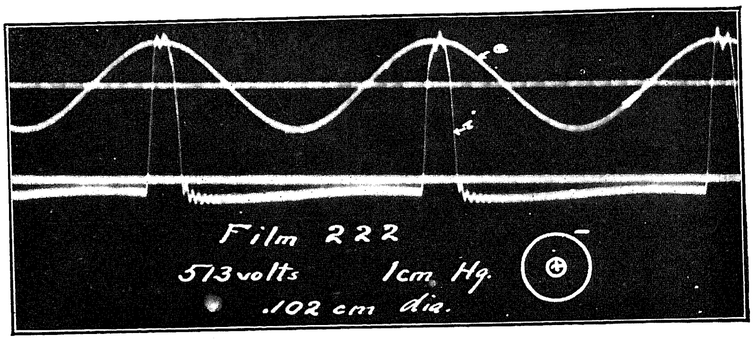


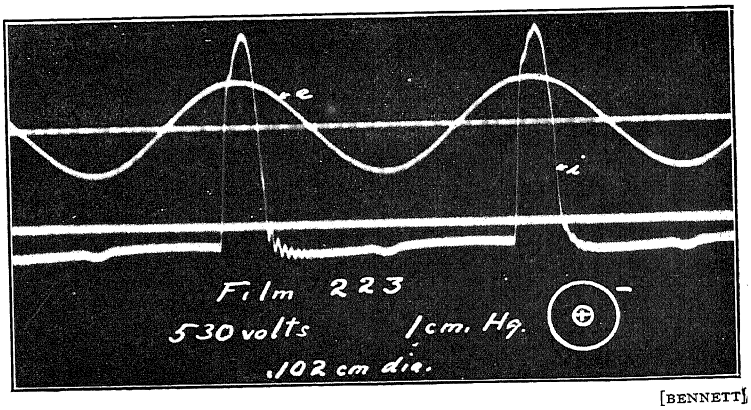


[BENNETT

PLATE LIV
A. I. E. E.
VOL. XXXI', 1913

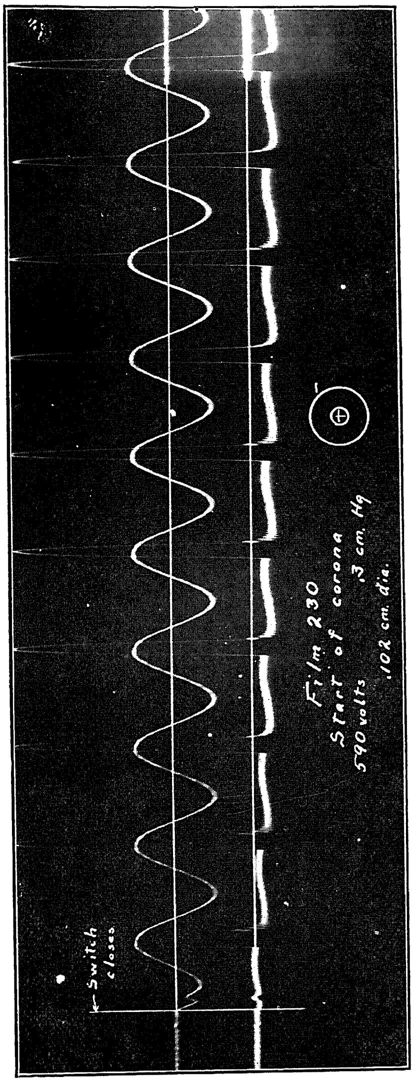


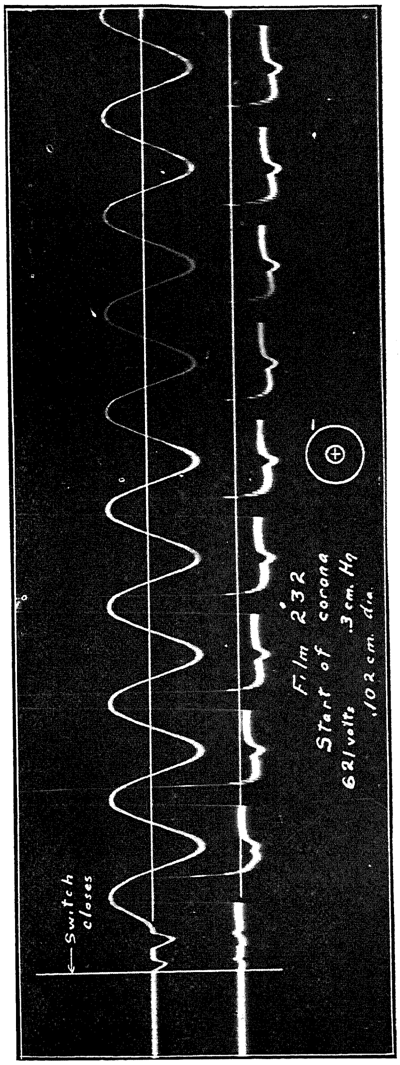




[BENNETT]

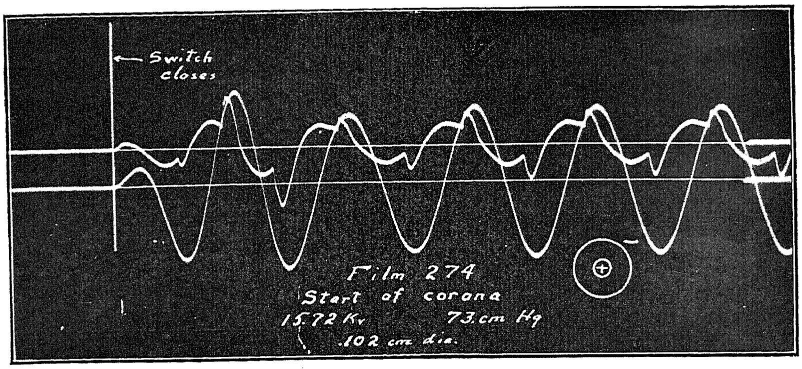
PLATE LV
A. I, E E.
VOL. XXXII, 1913

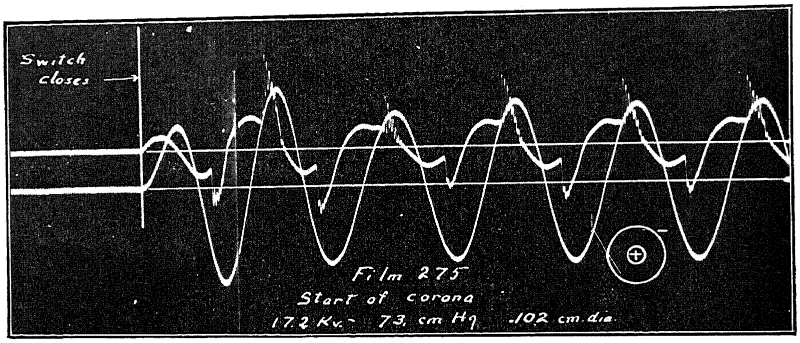


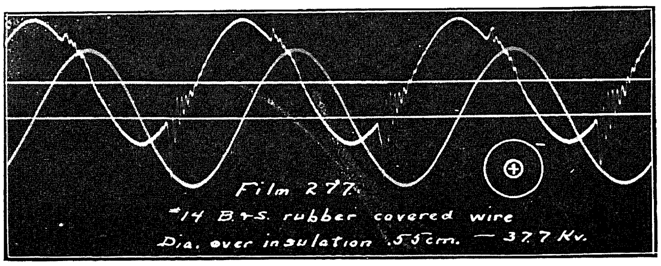


[BENNETT]

PLATE LVI
A. I. E. E.
VOL. XXXII, 1913







[BENNETT]

which these oscillograms were taken is so low that the charging current of the wire below corona causes a deflection of the current vibrator which is almost inappreciable.

At voltages slightly higher than the corona voltage the characteristic appearance of the current wave forms is shown by oscillograms 221 and 222. Copious ionization occurs for a short interval of time near the peak of the voltage during the half cycle in which the wire is cathode. There is no indication of copious ionization during the half cycle in which the wire is anode. After the cessation of ionization the current reverses and continues to flow in the reverse direction throughout the balance of the cycle. At higher voltages copious ionization also occurs during the half cycle in which the wire is anode, as indicated by the hump on the current wave form under the negative voltage peak on oscillograms 223 and 232.

Relation between the Air Pressure and the Corona Voltage. The relation between the air pressure and the impressed voltage at which the hump can just be detected in the current wave form of 0.102-cm. phosphor bronze wire is shown in Fig. 9. For the purpose of comparison, the values of the visual critical voltage for this conductor have been computed from the formula given by Peek for parallel conductors: These values are also plotted in Fig. 9, Peek's formula for the visual critical voltage e_v to neutral is

$$e_v = \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) 29.8\, r\, \delta \log \frac{s}{r} \text{ peak kilovolts} \qquad (7)$$

The two curves agree at atmospheric pressures and at pressures of about two cm. of mercury; at intermediate pressures the discrepancy is as high as 13 per cent.

The Start of Corona on Switching. The observation that copious ionization persists with decreasing voltage to a voltage several per cent lower than the voltage at which it is initiated with increasing voltage, gives rise to some question as to what occurs in the first few cycles after suddenly applying to a wire a voltage high enough to cause corona. Is the ionization as complete in the first half cycle after closing the switch as after many cycles? Or does it "build up" over a number of cycles? With impressed voltages much higher than the corona voltage, one would expect to find the corona fully developed at least not later than the second half cycle. With impressed voltages only a few per cent higher than the corona voltage it is not improbable that the steady state may only be reached after several cycles.

The following oscillograms show the current wave forms immediately after applying the voltage to the wire. These oscillograms were obtained with the Fig. 2 connections modified as noted below. All switching was done in the primary of the step-up transformer; that is, the wire was permanently connected to the higher tension terminal of the step up transformer, the supply voltage was adjusted to the desired value, and the voltage

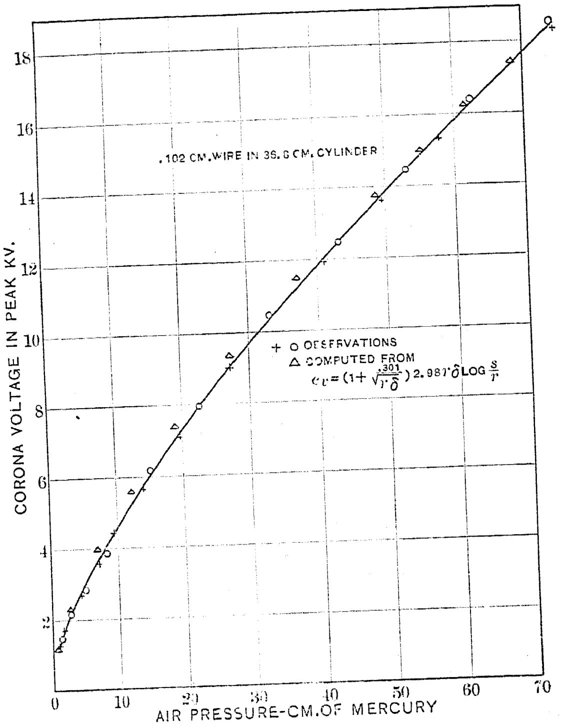


FIG. 9—RELATION BETWEEN AIR PRESSURE AND CORONA VOLTAGE

was suddenly applied to the wire by closing the main switch in the primary of the step-up transformer.

Oscillograms 230 and 232 were taken at an air pressure of 0.3 cm. of mercury, the former at a voltage about 12 per cent above the corona voltage. The potential vibrator and its series resistance was connected directly across the high-tension side of the step-up transformer for these oscillograms at low pressure. (For the switching oscillograms at atmospheric pressure, the potential vibrator was connected across the primary of the

transformer, as in Fig. 2). At these low pressures the positive current—from pipe to wire—is as large during the first half cycle as during subsequent cycles. The negative current, however, is low during the first half cycle and increases in value for the first eight cycles. This negative current does not necessarily indicate a current flowing in the primary from wire to pipe. It is probable that no appreciable current flows from wire to pipe, and that the apparent current in this direction is due to the interposition of the current transformer. That is to say, a unidirectional pulsating current flowing through the primary would account for the appearance of these films. The gradual increase of the negative current during the first few cycles may be attributed to the drift of the magnetic cycle in the iron to its permanent condition.

Oscillograms 273 and 275 were taken at an air pressure of 73 cm. of mercury, at voltages respectively 3 and 20 per cent higher than the corona voltage. An abnormally high voltage was invariably obtained on closing the switch; this causes excessive ionization during the first cycle and so masks the effect sought for at voltages only slightly higher than the corona voltage. The oscillations were damped out for oscillogram 273 by the use of the 0.94-megohm resistance in the primary of the current transformer.

Corona around a Rubber-Covered Wire. Oscillogram 277 shows the wave form of the charging current of a No. 14 B. & S. gage (diameter 0.16 cm.) single braided rubber-covered wire (diameter over all 0.55 cm.) at a voltage high enough to cause the formation of corona in the air around the insulation. This wire was mounted in the 36.8-cm. diameter wire mesh cylinder.

Note that the most striking oscillation in the current no longer occurs during the half cycle in which the wire is cathode, as with bare wires, but during the half cycle in which wire is anode.

IV—Summary

The features or characteristics of the corona around wires brought out by oscillograms of the charging and leakage currents may be thus summarized:

1. The distortion in the current wave form, which results from copious ionization at the time of the voltage peak, is observed simultaneously with the hissing sound and bluish discharge from the wire.

2. At air pressures below 20 cm. of mercury, copious ionization,—as indicated by the hump on the current oscillograms,—

sets in at a lower voltage during the half cycle for which the wire is the cathode than during the half cycle for which it is the anode.

3. From the oscillograms thus far obtained at atmospheric pressure it has been impossible to determine whether there is any difference in the voltage at which the distortion appears in the two half cycles, at pressures near atmospheric.

4. The boundary of the ionized region does not gradually expand outward from the wire with the increase in voltage during the half cycle. The loss of insulating properties in the air surrounding the wire must be conceived of as taking place with extreme suddenness. The evidence of this is the oscillation in the current shown on the oscillograms.

5. At air pressures near atmospheric, the asymmetry which results from the combination of the two conditions, namely, current carriers having different properties—positive and negative ions—and a field between unsymmetrical electrodes, manifests itself in two ways: (a) the loss of insulating properties by the air is much more sudden in the half cycle in which the wire is cathode, (b), at voltages slightly higher than the corona voltage, the power loss in the corona is greater during the half cycle in which the wire is anode. At higher voltages the percentage difference between the power loss during the two half cycles becomes extremely small.

6. At low air pressures, the asymmetry manifests itself as follows: (a) for a considerable range of voltages above the corona voltage copious ionization seems to occur only during the half cycle for which the wire is the cathode; (b) at these voltages the peak value of the current when the negative ions travel outward from the wire is far higher than when they travel inward toward the wire; the time of outward flow is, however, far shorter than the period of inward flow. Under these conditions, it is seen that the average values of the currents in the two directions may differ but slightly, while the root-mean-square values are greatly different.

7. At voltages above the corona voltage, copious ionization sets in at a lower voltage in the half cycle for which the wire is the cathode than in the other half cycle: in other words, copious ionization is initiated earlier in the cycle when the wire is cathode than when it is anode.

8. The quadratic relation between power expenditure in the corona and the impressed voltage, developed by other investigators for parallel conductors, is shown to apply to the single case of concentric cylinders for which the losses were obtained.

9. There is some evidence that several cycles may be required after applying the voltage for the conditions between concentric cylinders to reach a steady state.

10. A curve is plotted showing the relation between the air pressure and the voltage required to cause the distortion to appear in the current wave form.

DISCUSSION ON "THE ELECTRIC STRENGTH OF AIR—IV" (WHITEHEAD), "THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION" (STRONG), "LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR" (PEEK), AND "AN OSCILLOGRAPH STUDY OF CORONA" (BENNETT), COOPERSTOWN, NEW YORK, JUNE 27, 1913.

C. F. Scott: The papers that have been presented are part of a series which have been appearing in our transactions, building up a new literature. It was, I believe, fifteen years ago when the first paper on this subject recorded a number of experiments and tests by Mr. Mershon on the lines of the Telluride Power Company, in Colorado, and the tests were made jointly by the coöperation of Mr. Nunn of that company, and Mr. Mershon and the company he represented. That paper presented the effect of these losses and the method of measuring them, and the success of the tests was largely owing to the ability and ingenuity of Mr. Mershon in meeting new requirements under particularly difficult conditions.

The large fact presented was that above certain voltages there was corona loss as it has since been named. Professor Ryan became interested and undertook a study of these laws and conditions, and in a year or two came a paper by him giving the results of his laboratory work. Presently Mr. Mershon presented results of other tests in the field. Others have taken up the investigation. The paper presented this morning is the fourth paper in a series, another paper is the third paper in a series by the respective authors, dealing with this subject. Fifteen years ago a new fact was presented, and a new field of investigation was opened.

In the meantime, power transmission has gotten up away beyond the early voltages, and these matters of corona have become very important engineering factors and engineering limitations. New methods and instruments, both theoretical and investigative, are employed. New knowledge, new physical theories, are here applied, and this wonderful instrument, the oscillograph, is now applied to this very remarkable condition of measuring the charging or corona current in a little wire a dozen feet long.

This Institute as a whole, the engineering profession, and this whole department of high-tension transmission, are very much benefited by these papers, and I think I can speak for all when I congratulate and commend the authors on the excellent character of the work and its importance, both from the theoretical and the engineering point of view.

L. T. Robinson: The details of the work that has been done here are of very great interest; they will become of more and more interest as time goes on. But we have now heard a great deal of this work, we have many records, and perhaps at this

time it would be possible to go back a little to give the work an important practical application.

The one particular point that seems to be involved here, indirectly, is the question of the measurement of voltages. We have here, apparently, another means that may be employed, that is the measurement of voltage by the appearance of corona before the disruptive discharge takes place, and in many instances I think that would be a very valuable thing. We have, of course, other methods that are applicable in perhaps the majority of cases, but if I read the paper of Messrs. Whitehead and Fitch correctly, there appears to be a very sharp point where the phenomenon is observable, and if it would not be leading this discussion a little to one side, I would like to have something said by the authors and by the other gentlemen present as to what would be the advisable procedure in the case of different voltages and different conditions which must be met.

Professor Bennett's work, in which he speaks of the small angles between the currents in the transformers, of the nature of a degree, is very good testimony of the care with which he has looked over his results, and he has drawn the line rather finely, but it is quite evidently there, when you come to look for it. If we may digress just a little more, for an instant, I think it is a thing that may be taken as an indirect lesson by all of us, that is, we do a great deal of work and make lots of diagrams and make many figures on paper, etc., and make a lot of observations, but we do not half look at these things. If we examined them more carefully, we would not need to take so many observations. The small transformer to make the current observation in the oscillogram has been used many times, but I do not think the possibilities of operating in that way have been brought out so that it is quite generally appreciated. It might be of interest to say that in an ordinary electromagnetic instrument, for instance, a moving iron instrument, there is required in the neighborhood of from two to five watts to operate the instrument. In the oscillograph, although the current is rather large, the total energy required is rather small, and, unless I make some mistake in multiplying it, it corresponds to about 1/400th of a watt, so that there is a possibility of doing a great deal with suitable transformers, and no doubt the transformers could be much improved, and would be well suited for any other purpose, and the necessary corrections supplied. Even a sensibility of 1/400 watt leaves a good deal to be desired, because when you come to another instrument, that is the moving coil instrument of the type first commercially developed by Dr. Weston, we have something like 1/1000th of a watt as necessary to send it across the scale.

J. B. Whitehead: Mr. Robinson's suggestion that we consider the corona as a measuring instrument is one near to my heart, but I will not try to divert the discussion that way for a moment, but will get back to it later, perhaps.

Alan E. Flowers: In regard to electrical precipitation of suspended particles from gases, it ought to be emphasized here, that the subject has a very respectable history in physics, and that we are particularly indebted to the physicists of England for the ground work of the subject. C. T. R. Wilson showed that water vapor tended to condense upon ions and so precipitate. Lodge showed that foggy, out-door air could be cleared in the neighborhood of highly charged electrical conductors.

Out on the Pacific Coast, Professor F. G. Cottrell has been working on electrical precipitation for several years and has obtained some very satisfactory results. About a year ago, Professor R. C. Carpenter described a settling chamber or room, fitted with baffle plates, where the gas velocity was so reduced that something like 98 per cent of the dust was removed. The electrical methods were, at that time, capable of removing about 93 per cent of the dust. These figures are only approximate and any error in their statement should not be attributed to Professor Carpenter.

I should like to have from Mr. Peek more explanation of the large values for the "critical distance", which increases as the square root of the radius, does it not?

F. W. Peek, Jr.: Yes.

Alan E. Flowers: So that with a sphere of 12.5 cm. diameter, the critical distance attains values of nearly one cm.

In Professor Bennett's paper, attention should be called particularly to the use of the term "hypothetical gradient" and the author given our thanks for the use of the term. It seems to me that the values obtained by calculation, which we have been in the habit of using, must be subject to large corrections under corona conditions.

Taking up the question of voltage measurements raised by Mr. Robinson, I would like to call attention to an article published recently in England by Milner. In high-voltage measurement, probably the greatest difficulty is that due to the effects of frequency.

Milner's work throws much light on this point. He used the Braun tube to investigate the relation between the voltage and current in a small sphere gap, carrying an oscillatory high frequency discharge. Instead of voltage-time and current-time curves, Milner thus obtained volt-ampere curves, from which, assuming a sine current, the time curves were calculated. In Fig. 1, are shown the resultant curves for a discharge, oscillating at a frequency of 2,000,000 cycles per second. The initial peak of the volt-time curve is about 3000 volts; the voltage then drops to the arc value of about 35 volts. Succeeding loops all show an inital value of 300 volts, corresponding to the glow value, followed by the low arc value of 35 volts. The current showed a damping intermediate between the linear and logarithmic rate. The variation of the effective resistance in the oscillatory circuit doubtless has something to do with this rate of decay.

The high initial value of 3000 volts was obtained only once in each wave train, but the 300-volt glow value was necessary in each alternation, being followed by the arc value of 35 volts. These voltages are the same as the values one is accustomed to in work at commercial frequencies.

It would seem that this work is at least an indication that we may use the breakdown of air between spheres as a measurement of voltage, independent of frequency. These results also show the tremendous rapidity with which the fully ionized condition disappears.

Professor Bennett mentioned that in any cycle, corona ceases at voltages of 2 and 3 per cent lower than the value at which it began and also, laid some stress on the possibility that antecedent ionization, either in the same or preceding cycles, had something to do with the critical voltage. From Milner's work, one would conclude that recombination is too rapid for antecedent ionization to affect the critical voltage.

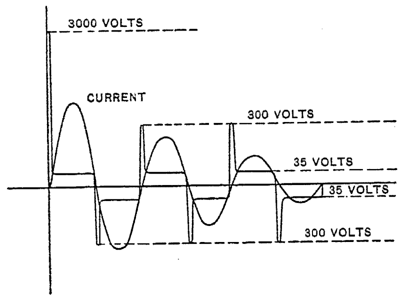


FIG. 1

On page 1790 and in the corresponding curves Fig. 7 it is shown that the voltage at which the corona begins in any cycle is appreciably lower, when the voltage is much in excess of the critical value. It might be pointed out that this, as well as the lower voltage for cessation of corona in any cycle, might with greater probability be ascribed to the temperature of the electrode surface. The bombardment of the surface being such, as to raise appreciably the temperature of a very thin surface film.

I would also like to ask Professor Bennett why the polarity, giving the greater power loss, is not the one allowing the breakdown at a lower voltage.

J. B. Taylor: It is interesting to note that Prof. Bennett has made use of a method which I suggested several years ago, though I believe Prof. Bennett has been the first to show records obtained by using it.

I refer to the differential connection of a current transformer in which the charging current, due to electrostatic capacity of

the wire on which corona is being studied, is balanced out by a condenser of proper capacity.

The construction of the balancing condenser should be such that it is free from corona. This leaves the corona current alone for recording or noting in instruments such as the oscillograph, ammeter, and wattmeter or other device.

I wish to ask if the doubling of the potential waves as shown in records 179 and 180 has any special significance, or does it result merely from a double exposure obtained accidentally in making the records.

W. H. Pratt: I am very glad Mr. Robinson raised the question as to the adaptability of methods of using corona for measuring high potential. It is a matter I have had in mind for some time and was hoping to hear at this meeting some facts which would either confirm or else change my opinion as to the possibility of making use of this phenomena in this measurement. I have nothing in detail to suggest, but would like to hear if there are others who have any ideas on that subject.

Alan E. Flowers: I would like to bring up another point, in regard to Professor Bennett's work in getting oscillographic records of the corona current, that is the possibility of using the Einthoven string galvanometer for the measurement of these very small currents. Its use would eliminate the difficulty of self-induction in the transformer and the oscillation that occurs when the corona discharge suddenly starts.

Paul M. Lincoln: I ask whether there is any one here who has made or observed or knows about the current of corona for high-voltage direct current. I think that will be an extremely favorable way to study corona and just why it is.

Alan E. Flowers: Answering Mr. Lincoln's question, I recall that Watson presented a paper at the Winnipeg meeting of the British Association for the Advancement of Science, in 1909, published in the *Electrician*, Vol. 63, page 828, Sept. 3rd, 1909. In this paper, experiments were described giving values of the corona current with direct current at voltages up to 100,000 volts. The critical voltages were the same as these found by Ryan for the maximum instantaneous alternating current voltages, when using the wire and concentric cylinder. For parallel conductors, out doors, under atmospheric conditions, much lower values were found and the critical voltages corresponded much more nearly to those found by Mershon at Niagara.

Paul M. Lincoln: What is the order of the losses which occur in that manner in comparison with those which occur in the breakdown with alternating current?

Alan E. Flowers: I do not recall the figures for the losses, but my impression is that the losses were of the same order as with the alternating current, though smaller.

John B. Taylor: I think Mr. Lincoln's point is very pat, and there is something wrong in the formula which puts frequency

directly into the formula. When we come to direct current the frequency should be taken as zero, and there is either a different set of conditions found to obtain or the formulas must be regarded as approximate, to be used only within a limited range of frequency.

Paul M. Lincoln: That is the object I had in mind in asking for the order of the losses with direct current. I thought probably the loss which would take place if the voltage were established on the wire and kept constant, compared to the loss which is due to the initial breaking down of the film is so small as to be entirely masked at frequencies of 60 cycles or thereabouts. That would lead the ordinary observer to believe that frequency enters directly as a factor, whereas as a matter of fact, at very low frequencies there is an appreciable loss.

John B. Whitehead: Before answering the one or two questions which have been asked specifically as to my paper I want to make one or two comments of my own on the papers of the other authors.

I want to call attention to some average values that are given by Professor Strong as to the size of gaseous ions and the velocities with which they move. If one wishes to get a conception of the mechanism suggested by the ionization theory for the conductivity of gases, these figures are rather suggestive.

Passing to Mr. Peek's paper, he will excuse me if I take another crack at his "energy zone." He knows there is nothing but good feeling in this. I should like to know why it is necessary to go to the extent of the suggestion he makes. If I understand it properly, the suggestion is, as you increase the voltage on the line, you are storing electrostatic energy in the electric field, and there finally comes a time when the medium immediately around the wire cannot stand any more energy. That is all right as far as it goes, but the thing which entirely robs the suggestion of any interest to me is that there is nothing constant about either the volume, density or length over which the discharge takes place, in other words, the zone is different in length for every size of the wire. That brings us back to where we were before.

I am particularly glad to read Mr. Peek's observations on pressure. I believe it is the first time they have been published in detail, and they, of course, offer a very interesting substantiation of the relation which he has given connecting the critical gradient with the density.

I also find that Mr. Peek is adopting the language of the ionization theory. At the top of page 1774, he suggests the mechanism by which the corona may be started, and that there may be free ions at the surface of one of the conductors. It is not necessary to assume that there are any ions at the surface. There are always a number of free ions in the air owing to the continual state of upsetting and recombining of the ions in the molecule. In normal air there are about 1000

free negative ions per cu. cm., and the number may increase four or five times under certain conditions. It is possible to increase the number enormously by various ionizing agents. When a difference of potential exists between conductors these ions are put in motion by the electric field. They are free charges and move in the direction of the gradient.

Passing to Prof. Bennett's paper, I want to express my very great admiration for the care with which the experiments have been performed and to state that I regard it as one of the most valuable contributions to this subject which we have had in some time. There are some points I want to raise in connection with it. On page 1784, in differentiating between the instant of ionization and voltage of copious ionization, the suggestion is made that there is some ionization due to the electric field before the instant of copious ionization. With the very sensitive method for observing the presence of ionization with the electroscope, I have never found the least evidence of any ionization preceding the actual instant of copious ionization.

Prof. Bennett says: "The hump is first detected during the half cycle in which the wire is anode and the cylinder cathode." If the wire is anode, the negative charges are moving in towards it and they are consequently moving into a region of intense field, and they will be accelerated more rapidly during their mean free path. This is in accord with the theory of secondary ionization. During the time which elapses between two collisions with molecules, if the ion has moved into a more intense field, it acquires greater velocity than if it had moved the opposite direction. Prof. Bennett points out that he was unable to observe this on the records, and refers to oscillogram 183. Oscillogram 183 appears to me to substantiate his statement. That oscillogram is as I would expect to find it, and I do not see any evidence on it of a starting of corona on the other half of the wave, when the wire is cathode.

Referring to page 1786; when slowly lowering the voltage, reference is made to the fact that the hump does not disappear from the current wave at the same voltage at which it began. I venture to suggest that this may be explained as a temperature lowering. The appearance of corona is sensitive to a change in temperature. The actual presence of corona, representing energy expenditure, elevates the temperature of the gas in the neighborhood of the wire. We have found through a long series of observations a number of discrepancies for which we could not account until we finally traced it to the elevation of temperature of the wire due to slight rubbing for cleaning purposes between observations. We found by letting it stand three or four minutes, to be sure that the whole apparatus came to constant temperature, that the trouble disappeared.

In paragraph 5, Prof. Bennett says that the oscillation in the current occurs when the wire is cathode to the cylinder. If the wire is anode in the neighborhood of starting of corona, the corona

is confined to a comparatively small region. When the wire is cathode, and you have the actual process of ionization or copious corona, you have a more free generation of ions due to the fact that the whole region is largely broken down, and so has high conductivity.

In paragraph 2, on page 1789, Prof. Bennett says: "With increasing impressed voltages, the instantaneous voltage at which the copious ionization sets in becomes smaller and smaller," and then refers to Fig. 7 to show the amount of that reduction. I am not sure that the temperature would account for as great lowering as he observes, but I want to suggest, at least, that it may be a possible explanation. It is extremely important to look for temperature variation.

At the top of page 1790 a statement is made: "The current is quite appreciable before the start of copious ionization." I venture to suggest that this is a residual effect, due to the foregoing corona. Recombination goes on with enormous rapidity, as indicated by the fact that the corona does stop. But this does not mean you have no ionization; the process of ionization is stopped, but there are plenty of free ions left and they constitute the current indicated by the slight accent in the curve of film 188.

Coming to page 1793, with reference to the great difference in the losses in concentric cylinders and parallel wires, I think the explanation is obvious,—This process of loss to my mind is made up of two factors, one is the process of ionization, or breaking down of the molecules, which undoubtedly requires energy. The other and larger part of the loss is due to the actual conduction current, caused by the passage of ions from one conductor to the other.

L. T. Robinson: Does not the loss vary directly as the frequency?

John B. Whitehead: I do not believe it varies directly. The difference in the paths of the ions in concentric cylinders and in parallel wires, would account for the difference in loss observed by Prof. Bennett. In the concentric cylinders you have perfectly straight paths for the ions, and very much shorter than in the widely scattered paths which approximately follow the electrostatic field between parallel wires. The actual loss must vary in some way with the frequency. If you get a breakdown on every wave, you pile up the loss with increasing frequency, but I do not believe there is a strictly proportional relation.

In regard to Mr. Robinson's suggestion as to measurements. In our laboratory we have been conducting experiments for the perfecting of the wire and cylinder apparatus as measuring instruments for some time, and I hope to be able to present the results of that investigation to the Institute in the near future.

The accuracy with which one can repeat observations on the formation of corona on a clean wire in a cylinder is very much closer than the possible control of the usual alternating-current

circuit. There is no question in my mind that if we can reduce the apparatus to a convenient form, so that it may be carried about, we have an instrument which is incomparably better, as regards final accuracy than either the needle or the sphere gap. A serious limitation of such an instrument is that for a given voltage there is only one size of wire. If several different voltages are to be measured with the same apparatus a number of wires are necessary. However they may be inserted readily and frequently, in a clean condition, corresponding to different voltages and I have not found that this is a serious complication. We have an apparatus, comparatively limited in range, as yet, with which we have worked for some time. Taking voltages almost daily since the first of October last year, and correcting for temperature and pressure, we have had no difficulty in checking these voltages over a wide range of conditions to a fraction of a per cent.

We are also investigating the surfaces of metals, as regards their permanency, looking to the possibility of eliminating the necessity for cleaning. We have not got far enough along with this to say what the best material would be. We are also trying various wave shapes, as the voltages measured have so far been considered, and I believe properly, to be the peak voltage, the highest voltage on the wave.

There is another limitation to such an instrument, that I regard as perhaps more serious than any and that is the fact that the observing instrument which so far has been found to be the most suitable for the observations is the electroscope, and the electroscope, unfortunately, is not a convenient instrument to carry about. It is not suitable for a shop test of high voltage. It is obviously impossible to use the visual appearance of the corona as the measuring instrument. To do this a room absolutely dark is needed and one must be in the room several minutes before he can see the first appearance of corona. We have developed another method of detecting the beginning of corona. We punch the outer cylinder full of small holes, and surround it with another cylinder so connected to the cylinder which forms the grounded side of the circuit as to make it sound-proof. Two openings in the outer cylinder are connected by two broad rubber tubes to two ear pieces strapped over the head. You can hear the corona start in a quiet room, and fix the point at which it does start on a clean wire just as closely as by looking at it. We have checked this with many tests made by two independent observers. I believe there are great possibilities in the concentric cylinder apparatus as measuring instrument.

I would like Mr. Flowers to give the references to Milner's paper and tell how these interesting curves at two hundred million cycles were traced.

With reference again to Mr. Lincoln's question as to experiments with high-voltage direct current, Watson's observations

were made with the induction static machine as the source of voltage, and while his observations were extremely interesting, I believe they are qualitative rather than quantitative. I do not think there should be any difficulty, however, in understanding the loss at continuous voltage if you go back to the idea which I have suggested, and which I think is unquestionably so, that a large part of this loss, not the principal part of it, is due to the actual passage of current between conductors.

Paul M. Lincoln: If the conception which Dr. Whitehead has just given is correct, our law of loss due to heating needs revision. Frequency does not apply there.

F. W. Peek, Jr.: Answering the questions asked in reference to variations of corona loss with frequency: The greater part of the loss over the commercial frequency range is a per cycle loss or varies directly with the frequency. There is also added to this a small constant loss independent of the frequency.

The complete loss equation may be written:

$$p = k\ (f+a)\ (e\text{-}e_0)^2 \text{ kilowatts per kilometer of circuit.} \qquad (1)$$

Then at zero frequency f becomes zero and the loss is

$$p = k\ (a)\ (e\text{-}e_0)^2 \text{ kilowatts per kilometer of circuit} \qquad (2)$$

The constant a is comparatively small.

Therefore where f is comparatively large a becomes negligible and the loss may be written:

$$p = k\ f\ (e\text{-}e_0)^2 \text{ kilowatts per kilometer} \qquad (3)$$

The equation is generally written in the form (3) for convenience in working at the higher commercial frequencies near 60-cycles and practical size of conductors. When I first gave this equation in my paper in 1911* I stated it did not mean zero loss on direct current. The zero frequency loss indicated in (2) is not necessarily the d-c. loss, but one would expect the d-c. loss to be higher. There must be loss on the d-c. because as soon as a given flux density is reached the air must break down. This requires an expenditure of energy. There must also be a flow of energy to keep the air in this broken down state as the ionized particles move away. Some three or four years ago I made some measurements of corona loss on a wire in a tube. I found that if air were sent through the tube the loss increased with increasing air velocity. The faster the broken down air was moved away the greater the loss.

Watson has made loss measurement of d-c. corona on wires. While these loss measurements are rather qualitative than quantitative, they indicate a d-c. loss of about $\frac{1}{4}$ to $\frac{1}{2}$ the 60-cycle a-c. loss at the same maximum voltage.

I have frequently used corona as a means of measuring very high voltages as a check on other methods.

*Law of Corona, TRANS. A. I. E. E., Vol. XXX, 1911, p. 1889.

Sometime ago I found that the needle gap varied a great deal from time to time at constant temperature and pressure. This variation is caused by humidity. Around the needle gap there is a great brush discharge before spark-over. The water in the air which exists as a gas is probably changed into vapor or a "fog" around the needle points by the brush discharge. This has the effect of increasing the size of the conductors and causes a higher spark over voltage. Humidity has no effect on the starting point of corona, or spark over on spheres, because there are no brushes to cause change from gas to vapor. I mention this because it has a bearing on precipitation.

Prof. Bennett's loss investigation confirms the "quadratic law" which was first derived by me in 1910, and given in discussions in Jan. 1911 and more completely in the "Law of Corona," June 1911. The difference is quantitative. This is because of the small size of wire used, which is much smaller than any used on commercial lines. Where the wire is smaller than about 0.25 cm., e_0 is larger than that expressed by the simple practical equation, and I have given a more complete equation to cover small wires. This complete equation, however, is of theoretical interest.

For use over a wide range of frequency and radius of conductor, it is:

$$p = 241\,(f + 25)\sqrt{\frac{r + \frac{6}{s} + 0.04}{s}}\,(e - e_d)^2\,10^{-5}$$

$$e_d = g_d\,m_0\,r \log_\epsilon \frac{s}{r}$$

$$g_d = 21.2\left(1 + \frac{0.3}{\sqrt{r}}\,\frac{1}{1 + 230\,r^2}\right)$$

Even before the practical size of conductor is reached, $g_d = g_0$ and is constant, or e_0 is constant for all practical sizes. For the smaller sizes g_d increases and finally at zero radius $g_d = g_v$. Prof. Bennett's data should check substantially the above equations.

These equations derived from measurements over a frequency range of 20 to 130 cycles and wide conductor range reduce to (3) for practical size of conductor, spacing, and frequency.

It must always be remembered that there should be no loss below e_v with perfectly smooth conductors. The loss below e_v therefore varies from day to day depending upon irregularities and follows the probability curve. It is not of much practical importance to know this loss, as the storm loss limits the maximum voltage to about fair weather e_0.

In regard to Dr. Whitehead's objection to the energy zone

theory: This theory has helped me in deriving formulas and has therefore been useful. For instance—I probably would not have been able to write the formula connecting visual gradient with radius and pressure if I had not looked upon it in that way. The electron theory is of a great help and will be a greater help, but it is not possible to explain everything by it at the present time.

Edward Bennett: With reference to the question about the double appearance of the voltage curve on films 179 and 180, I would say that is due to a fault in the reproduction of the film. The curve is rather broad.

The use of the string galvanometer has been suggested because it has been assumed that the resistance of the current transformer is excessive. By reference to Fig. 3, however, it will be noted that the resistance of the current transformer and vibrator is only 0.02 megohms, whereas the capacity-reactance between the wire and cylinder in series with which it is connected is 90 megohms, so that the voltage consumed in the current transformer will be a small fraction of one per cent of the total impressed voltage. It is true that the current sensibility of the string galvanometer is extremely high, but it must be remembered that the current sensibility has been obtained at the expense of a long period of vibration, so that the string galvanometer would be absolutely unable to reproduce frequencies of the order we have to reproduce in this case.

With reference to the statement during the discussion that film 183 shows the distortion in the current wave form only when the wire is anode, I would state that it is extremely difficult to detect in the reproduction any distortion in the current wave form during the half cycle when the wire is cathode, but such a distortion can be readily determined on the original films.

John B. Whitehead: It shows here on the reproduction of the film when the wire is anode and not when the wire is cathode.

Edward Bennett: The difference between the appearances of the distortions in the current curves, which makes it difficult to determine whether there is a certain range of voltage over which the distortion occurs only during the half cycle when the wire is the anode, or vice versa, is pointed out in the discussion of film 183.

John B. Whitehead: The only point I want to make is if you have that kick in the current wave, its amplitude is much greater than the amplitude of the disturbance on the other side. It indicates to me if you carry the voltage on down it would simply show the fact on the film as it is shown here.

Edward Bennett: I do not think that necessarily follows, when you consider the other fact developed by the oscillograms, namely, at higher voltages copious ionization starts earlier in the cycle when the wire is cathode than when it is anode. The

direction of the gradient when ionization is first observed, is still, I think, an open question.

With reference to the method of measuring voltages by means of corona, I understand that Professor Ryan has done a great deal of work in which he uses a measuring instrument comprising a conical conductor in a concentric cylinder. This is the only type of instrument with which it would be feasible to measure varying voltages. Suppose you wanted to determine the peak voltages due to surges, etc. It is not feasible to change the inner conductor, as has been suggested, but a conical inner conductor may be used and the point on this conductor at which the corona terminates may be noted. Whether this can be used as an exact indication of the highest voltage, remains to be determined.

It is my understanding that all the equations expressing relation between loss and voltage, between the critical gradient and radius of conductor, etc., are not rigorously exact but are approximate equations.

Messrs. Whitehead and Peek are to be congratulated upon the manner in which they marshalled and analyzed a very large mass of experimental data, and from this have evolved the few elegant relations embodied in the equations expressing the interrelations between power loss, diameter of conductor, air pressure, and impressed voltage. The extension of these empirical relations between the critical intensity, the density factor and the diameter of conductor, which were first worked out for the case of cylinder conductors, to the case of spheres, is a distinct contribution to the subject.

In addition to this contribution the third paper is entitled "A theory of rupture." This theory is advanced in the attempt to account for a discrepancy between our preconceived notions and experimentally determined facts. The preconceived notion is that the computed electric intensity or gradient at which a gas gives experimental evidence of breaking down ought to be a constant. The fact is that the computed gradient, the gradient computed on the assumption that there is no accumulation of charge around the conductors is not a constant, but becomes larger and larger for conductors of smaller and smaller diameters.

After developing the simple relation $g_v = g_0 \left(1+\frac{k}{\sqrt{r}}\right)$ and noting from this that the computed gradient is always constant and equal to g_0, at a distance of $k \sqrt{r}$ from the surface of the conductor, the simplicity of the relation seems in some way to lead to the conclusion that failure does not occur at the surface, but only after "rupturing energy" has been stored around the wire in a zone between the wire and this hypothetical cylinder at which a constant hypothetical gradient is obtained.

It must be remembered that an analytical expression can be found which will express the distance between the surface of

the conductor and the point at which the computed gradient at the voltage of rupture has any other constant value, as 25 or 20 kilovolts per cm.

Does this fact, however, the fact that an expression can be found for the distance from the surface of conductors to a point where the computed gradients are constant, warrant the interjection of the notion of an energy storage zone? It must be recognized that in the hands of the author of the theory, the notion of the energy storage zone has been very fruitful and has led to some very simple relations, but in the hands of others, or in the mental processes of others, of whom I am one, the notion of an energy storage zone is absolutely fruitless and barren. This may be a fault, not in the notion, but in the mental processes of those to whom the notion is fruitless. To me it is an incident that the expression for the distance between the surface of a conductor and the point at which the gradient is 29.8, or 31, or 33.6 kilovolts, assumes a simple form. I have no real quantitative explanation to offer for the relations observed, but in my estimation the fruitful explanation will be based upon statistical relations to be expressed in the language of the atomic structure of electricity.

Alan E. Flowers: The article by Milner was published in Nov. 1912 in the *Philosophical Magazine*, Vol. 24, page 709.

John B. Whitehead: How was that curve obtained?

Alan E. Flowers: Results were obtained by the use of the Braun tube and the sharply defined cathode ray pencil, produced by having two metallic screens, each pierced by a small hole in the center and along the line of the axis of the tube and also perpendicular to the cathode surface, the screens also forming anodes in the tube. Part of the cathode rays, proceeding in a direction normal to the cathode surface, passed through these

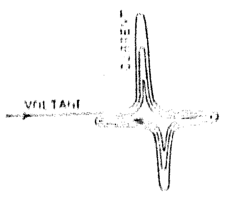


FIG. 2

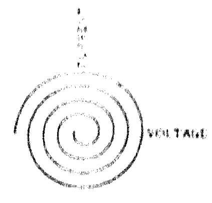


FIG. 3

two holes and were deflected by the magnetic and electric fields of the discharge circuit. The oscillating current through the sphere gap was assumed to be a sine wave and was produced by an induction coil. The primary on this induction coil was in series with the primary of another coil, whose secondary supplied the discharge in the tube, thus making the cathode ray pencil occur in synchronism with the current in the gap circuit. The oscillating current through the gap passed also

through a coil whose axis was at right angles to the tube and "cathode ray pencil" and produced a magnetic field tending to deflect the cathode pencil vertically. Plate electrodes so set that the electric field between them tended to deflect the cathode pencil horizontally, were connected either across the sphere gap or across the supply condensers and consequently deflected the pencil in proportion to the gap voltage or the total voltage of the oscillating circuit. The cathode pencil fell upon a willemite screen and was photographed. In this way, crossed and spiral curves were obtained, such as are shown in Figs. 2 and 3. The photograph showed rather a wide band. A line was then drawn along the middle of the photograph trace and this line-curve analyzed to give the curve shown in Fig. 1 (p. 1813). The actual record is thus the volt-ampere characteristic, from which, assuming a sine current, the time curves may be calculated. The volt-ampere characteristics obtained when the total oscillating voltage was used, were of spiral or elliptical form, thus checking the assumption of the sine wave discharge.

John B. Whitehead: The Braun tube is perfectly well known.

Alan E. Flowers: This method of getting a volt-ampere curve is, however, new, and gives extremely useful information under the very difficult conditions of extremely high frequency.

William J. Hammer: Professor Whitehead referred to the effect of particles of dust, on the path of the flow; and he also referred to some experiments conducted on the surfaces. It seems to me that the surface characteristics of metal is a matter to which not sufficient attention has been given, where particles may rest on the surface, where the surfaces are irregular or vary in their constitution or formation, or are exposed to effects of oxidation.

I speak of this because of some experiments I made some years ago in conjunction with Professor Campbell of Columbia, at which time we made a large number of photomicrographs of metal surfaces and carried out a series of observations upon the physical characteristics of the metals themselves. In certain of these experiments sheets of various metals were put in a trough, which was oscillated for a considerable time. This trough contained lignum vitae balls and powdered pumice stone and the surfaces of the metals were roughened slightly, but very evenly, and many photomicrographs were then made and studied. Many experiments were made upon these metals to show their surface characteristics. As an illustration, I will mention one of these experiments made upon aluminum and zinc. I poured a little collodion on the two surfaces, and as soon as it dried, the collodion peeled off the zinc but it stuck so fast to the aluminum I could not get it off with a penknife blade. There were many other experiments made at the time which were of a good deal of interest and demonstrated that these

surface characteristics of the metal itself are frequently very important.

John B. Whitehead: It has been known for some time that the corona-forming voltage does not vary at all with the material of the conductor. However, the condition of the surface of the conductor does have a great deal to do with the accuracy and sharpness with which the corona will appear with increasing voltage. Anything in the nature of a dust particle or surface inequality is capable of upsetting the observation. With the visual observation you can usually detect a surface imperfection as a slight brush discharge before the whole uniform corona breaks out. We have studied different surfaces, to find out which are the most permanent as regards oxidation or any other process which may upset the character of the observation.

Harris J. Ryan (by letter): As a contribution to the discussion of Professor Bennett's corona paper, Fig. R1 is submitted. It is the cyclogram in Fig. 6, page 545, Vol. XXII of the 1903

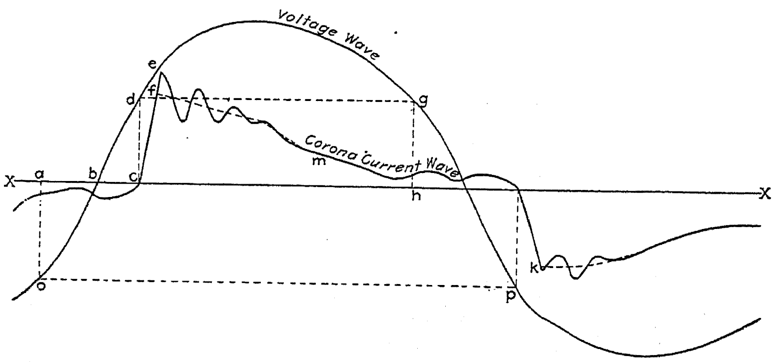


Fig. R1—Developed from Cyclogram Fig. 6, Page 545, Vol. XXII, A. I. E. E. Transactions

Transactions. This cyclogram was taken by the method specified as number 1 in the present paper, *i.e.*, the coils of the cathode ray cyclograph were "connected between the wire" and the high-tension transformer which charges the wire in the concentric wire and cylinder outfit. The following items taken from this cyclogram are in substantial agreement or non-agreement with corresponding items in the paper:

1. The characteristic polarity difference in the wave forms of the corona currents when entering and when leaving the wire as discovered by Professor Bennett is here quite in evidence and in complete agreement with oscillogram No. 189. Thus it is known that the upper half wave was formed when the wire was negative and the lower half when it was positive.

2. The voltage required to start corona was 17.5 per cent greater when the wire was positive than when it was negative.

3. It shows that the wire positive, exceeds the wire negative

duration of copious ionization by 12.5 per cent and that the rate of such negative copious ionization is 62.5 per cent in excess of the rate of positive copious ionization.

4. That the impact oscillation superimposed upon the corona conduction current circulates only in a local circuit, is established by the following facts that appear in the original composite cyclogram reproduced in Fig. R2. The cyclogram LC records the composite condenser and corona conduction current passing between wire and cylinder. The cyclogram CC records the charging current through a non-corona-forming air-core condenser of equivalent capacity connected in multiple with the wire-to-cylinder condenser. The difference between these two

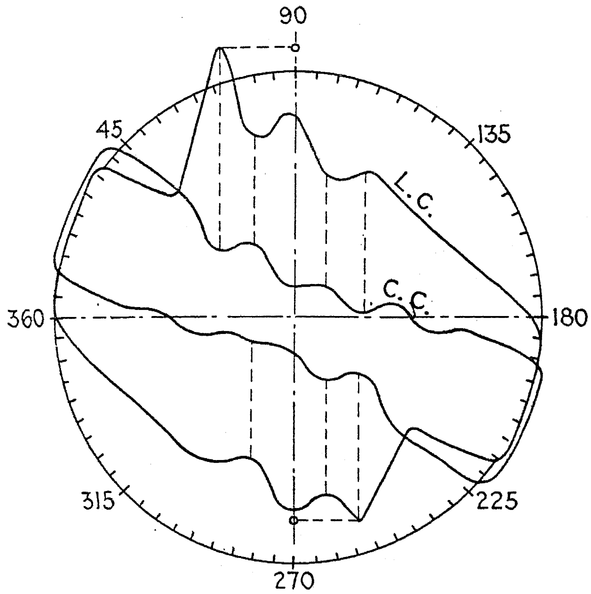


FIG. R2

is the corona conduction current transferred to rectangular coordinates in Fig. R1. Each cyclogram in Fig. R2 records a damped oscillation. These oscillations are seen to occur simultaneously, to have about equal magnitudes and to be in phase apposition. The scheme of connections used for the wire-to-cylinder and control condensers, the cyclograph coils and their switch to throw them in series with either condenser, is given in Fig. R3. It is seen at once that a local circuit is always formed through the corona wire and control condenser C_1 and C_2 and the cyclograph coils; it is seen also that when the coils are switched from the wire to the control condenser they are reversed with respect to this local circuit, though they remain direct with respect to the supply voltage. Under these circumstances

the same current circulating in this local circuit would necessarily be recorded in the line circuit through C_1 in one phase and that through C_2 in corresponding phase apposition. Since this is precisely what appears in the cyclograms of Fig. R2, those oscillations therein are one and the same. It follows, therefore, that the same process that subtracts the equivalent or control condenser current from the total corona-condenser current to the wire, isolates the sum of *once* the corona current and *twice* the impact oscillation, current. Is not this the case also in the author's oscillograms such, for example, as No. 189? The frequency of this oscillation is 2500.

5. This cyclogram shows clearly a continuation of the corona conduction after the collapse of the corona envelope and while the voltage wave is passing through zero. In many cyclograms made with conditions differing widely, substantially this same thing was always observed. See cyclogram samples hereof in Figs. 5 and 6, pp. 116 and 117, Vol. XXIII of the 1904 TRANSACTIONS. The cyclograph was, however, connected directly to the wire. The author observed the opposite effect at cylinder. It is a difference that invites speculation as to the cause. It seems hardly likely due to methods of measurement, and may possibly be due to the natural facts.

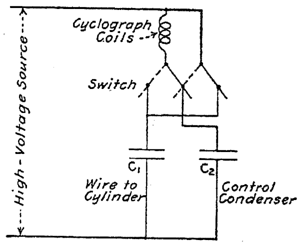


FIG. R3

6. The corona current wave of Fig. R1 resulting after discarding the superimposed parasitic oscillation must be further corrected for the excess of the wire capacity current with respect to the equivalent condenser current due to the increase in the capacity of the wire-to-cylinder condenser during the existence of the conducting corona envelope covering the wire. This is not a large correction and as yet our knowledge is not sufficiently complete to apply it with exactness.

7. Ten years ago we did not know about the importance of cleaning the wire to get consistent results. Consequently we obtained the sharp, sudden, copious ionization recorded in Fig. R1 only at the outset when the wire was " clean." In a series of studies extending over six months the wire was never cleaned. The cyclograms taken and preserved in the latter stages of this work all show a much more gradual start and formation of the copious ionization.

8. With the aid of the cathode ray power oscillograph, using electrostatic control only, in which all material self-induction is absent, I have often in recent years made a direct study of corona phenomena on short high-voltage lines and have never found any evidence of the presence of these oscillations. See a sample set of such corona power cyclograms in Fig. 6, p. 1096, Vol. XXX of the 1911 TRANSACTIONS. Nevertheless we must not fail to realize now the great importance of Professor Bennett's

discovery. Certainly we have in this new truth a clear indication of what we must expect to find in an open-ended 150-mile transmission line subjected to heavy corona at the middle*. Again it is hereby made evident that any corona-forming over-voltage to which a transmission may be subjected accidentally can become a source of high-frequency effects that we find are always hard on insulators subjected also to corona, for at high frequencies such coronas are extremely hot and most effective for puncture or fracture.

9. In reference to the happy distinction drawn by Professor Bennett between hypothetical and actual gradients, I have tabulated below the voltage duties of the individual units in a six-unit suspension insulator string supporting a No. 0000 B. & S. gage line cable, 3.5 feet from the ground, so that corona could be

No. of insulator units	Total voltage to ground	
	54,000	100,000
	Per cent of total	Per cent of total
Ground		
1	11.7	11.7
2	11.7	11.7
3	13.3	21.6
4	22.0	15.0
5	22.3	21.6
6	19.0	18.3
Conductor		
	Total 100.0	100.0

started on such cable at about 63,000 volts to ground, altitude 3900 feet, and developed in profusion when this voltage was raised to 110,000. Such voltage duties are given for the sub-corona voltage of 54,000 and the high over-critical corona voltage of 100,000.

Several tests of this sort were made. Always corona was observed to modify the original form of the field, *i.e.*, to change the hypothetical gradient. It should be said that the insulator units did not develop appreciable visible corona at the upper voltage, with the following exception: unit No. 6, next to the line conductor, showed a very faint glow visible in full darkness on the under side adjacent to the "pin". The line conductor was, of course, ablaze with corona. The measurements, although made by methods in which we have had little experience as yet, are believed to be substantially correct.

*E. L. West, *High-Voltage Line-Loss Tests*, A. I. E. E. TRANSACTIONS, Vol. XXX, 1911, p. 77.

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 9, 1913.

EFFECTS OF ICE LOADING ON TRANSMISSION LINES

BY V. H. GREISSER

In a number of papers on transmission line subjects, which have been presented before this Institute, mention has been made of the fact that wires hung from suspension insulators did not maintain their position in the same manner as when pin type insulators were used. It is assumed that this fact has not been sufficiently covered to show the importance of such change of condition of equilibrium, and therefore a record of actual experience and tests may prove of interest to engineers and operating companies. A brief description of the tower line experimented with will assist in making the subject clearer.

In the latter part of 1911, The Washington Water Power Company, of Spokane, Washington, finished the construction of, and placed in service, a double circuit tower line about 28 miles (45.1 km.) long, between its Little Falls power station and the high-tension, step-down substation near Spokane.

The type of tower used is shown in Fig. 1, and it is to be noted that the conductors on each side of the tower were spaced seven feet (2.13 meters) from each other in a vertical plane. Each conductor was a nineteen-strand, 270,000-cir. mil (136.8 sq. mm.) aluminum cable. Two $\frac{3}{8}$-in. (0.953 cm.) diameter extra galvanized Siemens-Martin steel cables were attached to the top of the towers for lightning protection, and it was interesting to find, during tests on a tower, that these cables also have a very great effect in adding stability to the construction of the line as a whole. Each cable was suspended from the ends of the crossarms by means of four 10-inch (25.4 cm.) diameter insulator units as shown in Fig. 2, the length of the

complete insulator and cable clamp being 34¼ inches (87 cm.) from the center of cable to the eye at the end of the crossarm.

The cable clamp (also shown in Fig. 2) consisted of two pieces of treated hardwood with companion grooves in which

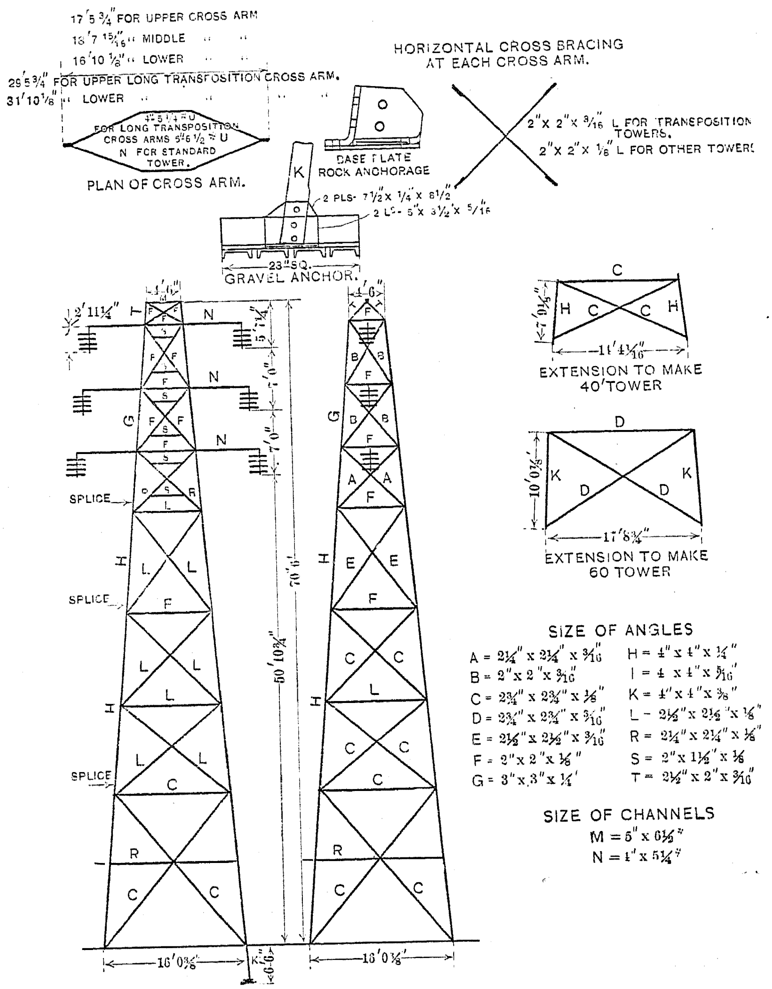


FIG. 1—STANDARD TOWER.

the cable was clamped as shown in the drawing, the hardwood being used in contact with the aluminum, to prevent any abrasion after the clamp was tightened.

An arcing rod ¼ in. (0.635 cm.) square was placed in a groove

on the upper side of the top half of the wooden clamp, this rod being intended to act in protecting the cable in case an insulator flashed over. There have been so few of such insulator flash-overs up to this writing that no extended data are available as to the usefulness of the arcing rods, but in the cases in which flash-over occurred, the cable was protected from in-

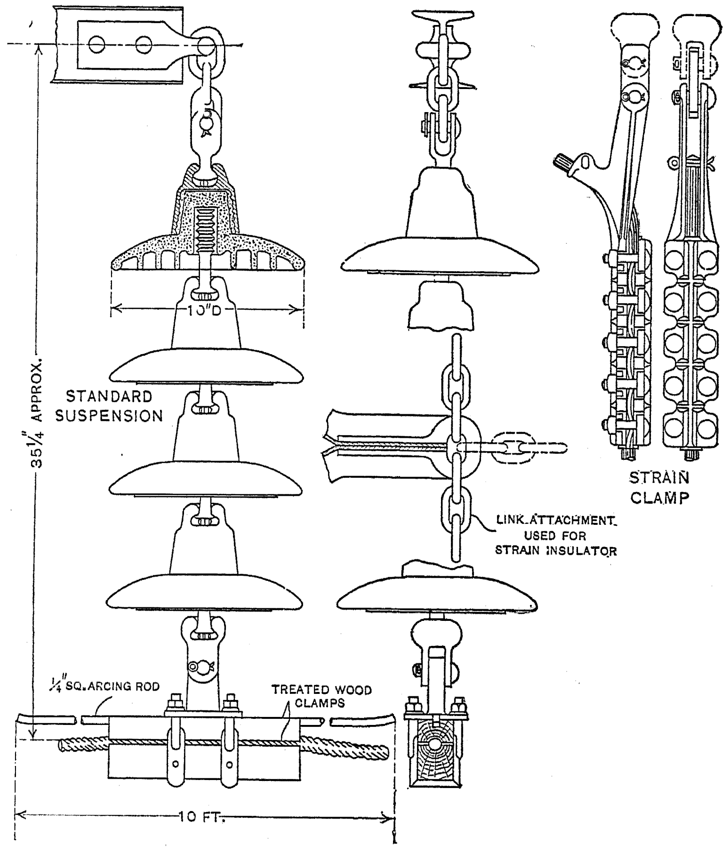


FIG. 2

jurious pitting or burns. A small strip of sheet aluminum was used to connect the cable to the metal parts of the clamp and lower insulator unit to prevent burning or digesting of the wooden parts.

The standard span was 750 feet (228 m.), but in 26.52 miles (42.7 km.) of actual tower line, 225 towers were used, making an average of about 625 feet (190 m.).

The heights of towers, weights and number used were as follows:

Height to lowest suspension from ground stub	Number used	Weights without footing
40 ft. (12.2 m.)	10	4315 lb. (1960 kg.)
50 " (15.2 m.)	189	5324 " (2420 ")
60 " (18.3 m.)	10	6390 " (2890 ")
50 " (15.2 m.)	16	6467 " (2930 ")

The last 16 towers enumerated above were transposition towers.

All the material of towers, insulators and conductors was tested and inspected at the factories.

This line was put into operation without trouble, and operated thus until about the middle of December, 1911, when numerous short circuits occurred without any apparent cause. Regular patrol had been maintained, but during a few days of fog and frost conditions the short circuits occurred so frequently as to make the line almost useless. Though a large number of men were almost continuously along the line, it was some days before the cause of the trouble was located, in fact not until the trouble had ceased could enough evidence be accumulated to show the real cause.

It was then found, during the fogs, when hoar frost and ice formed on the cables, that, upon the weather becoming warmer, the frost and ice would fall from the cables, but not from each span at the same time, and the loaded spans would increase their sags and at the same time decrease the sag in adjacent spans and deflect the suspension insulators until a new condition of equilibrium was established, which caused short circuits between wires. A test was made to show this fact, by loading the bottom wire of one span with seven bags of rock equally spaced and which fairly represented the load of ice that had been known to accumulate upon the cables.

The effect upon the loaded span and the adjacent spans was rather startling, since the loaded span sagged down to within 13 ft. (3.96 m.) of the ground, the increase in sag being approximately 20 ft. (6.1 m.) in a span 733 ft. long (223 m.).

The bottom cables of unloaded spans at either side became more taut, and thus reached a position within two inches (5.08 cm.) of the middle cable at the centers of those spans, the middle

cables being normally seven feet (2.13 m.) above the bottom ones.

The insulators supporting the loaded span were deflected about 50 degrees towards it.

Thus it will be seen that any span on which the heavy ice load had not dropped, and which had adjacent unloaded spans, would probably short-circuit a line with vertical spacing of wires as described above.

A number of observations were made on the line when sleet, snow or frost was on the cables, and the unstable conditions of the spans observed were so startling that it was decided to make a series of tests to determine what the principal features were that produced the changes in sag.

It was desired to ascertain:

First. The influence on the loaded span of the elasticity of the cable.

Second. The effect of swing of insulators.

Third. The effect of using strain insulators at frequent intervals.

Fourth. The combined effect of the above conditions.

These tests were made over what was considered at the time a rather large range of equivalent ice loading, but subsequent information shows that weights of ice greater than the maximum used in these tests must be provided for, in designing lines for some localities.

Reference to Fig. 3 will show the experimental line constructed. A level stretch of ground was selected and five spans of line were erected, using six 60 ft. (18.3 m.) cedar poles 750 feet (228 m.) apart in a straight line.

Heavy crossarms were attached at the top and spaced seven feet (2.13 m.) to reproduce the same spacing of arms as on the steel towers. Four units of the disk insulator type were attached to the ends of the arms, these units giving identical suspension with that on the towers. The insulators weighed about 46 lb. (20.9 kg.).

Aluminum cables of 270,000 cir. mils (136.8 sq. mm.) section (the same as on the towers) were then strung on the insulators, the ends being dead-ended at the first and sixth poles. This cable weighed approximately 1315 lb. (595 kg.) per mile (1.61 km.), with an average ultimate strength of 24,000 lb. (10,900 kg.) per square inch (6.45 sq. cm.) and an elastic limit of approximately 14,000 lb. (6350 kg.) per square inch (6.45 sq. cm.).

The cable was strung according to a temperature-tension curve based on a maximum condition of stress of −30 deg. fahr. (−34.4 deg. cent.) with ¼ in. (0.635 cm.) of solid ice around the cable and with a 60-mile (96.5-km.) (actual velocity) wind blowing at right angles to the line. Under this condition the cable would be stressed to the elastic limit as given above.

The crossarms and poles were rigidly guyed, with turnbuckles in the guys to maintain poles and arms in a constant position.

Marker poles were set up at the center of each span to measure the sags and changes in sags. Transits were used to determine any movement of arms or poles.

During the tests described below the temperature ranged between 58 deg. fahr. (14.4 deg. cent.) and 72 deg. fahr. (22.2 deg. cent.), but the influence of this change of temperature

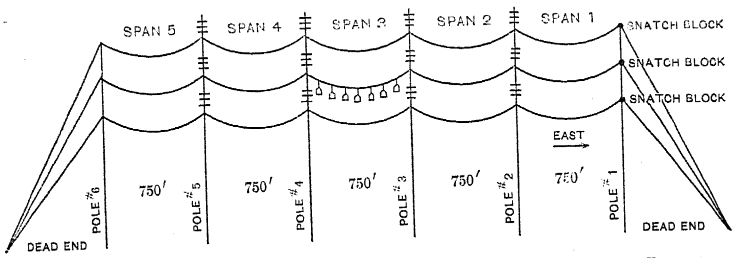


FIG. 3—EXPERIMENTAL LINE CONSTRUCTED NEAR JAMIESON, WASH., TO DETERMINE THE EFFECT OF ICE LOADINGS ON LONG SPANS OF ALUMINUM WIRES, USING SUSPENSION AND STRAIN INSULATORS.

was found to be so small as to be beyond the accuracy of the test. No wind was blowing at the time of taking readings.

To reproduce as nearly as practicable the condition of ice loading on the conductors of the steel tower line, seven concentrated loads were hung from the conductor, equally spaced in the span.

This is not an exact representation of ice load on a cable, yet loads so spaced would give results comparable with those under operating conditions, since it has been observed that ice or sleet forming on wires does not do so with mathematical uniformity.

The vertex of the span is shown plotted in the curves, and is measured on all three cables from the same common point.

It is also to be remembered in this connection, that the three conductors were normally seven feet (2.13 m.) apart in the vertical plane.

First Test. The middle cable in span 3 (see Fig. 3) was loaded with various amounts to represent ice loading. The sags of each span, insulator deflections, and the distance were measured from the nearest pole to the point where the middle cable crossed the cable below.

This is equivalent to having strain insulators every five spans with ice loading on the middle span and with the other spans bare.

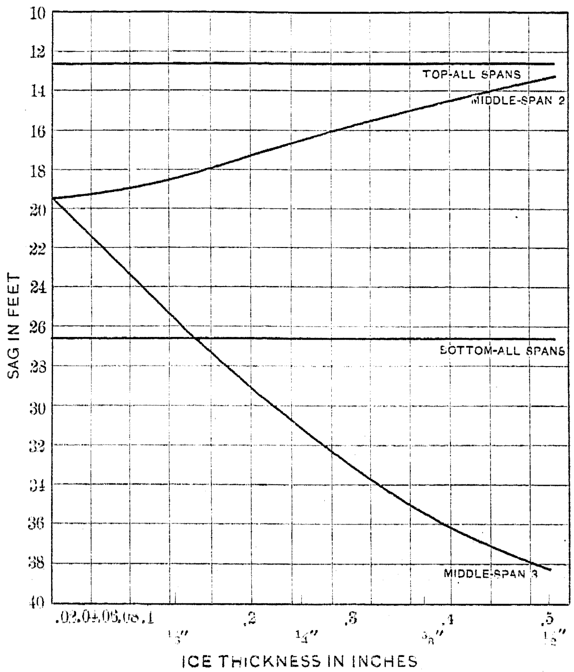


FIG. 4—FIRST TEST.
Middle wire in span 3 loaded.

The results are plotted in Figs. 4, 5 and 6.

Second Test. The middle cable in span 1 was loaded, this being a test having the equivalent of a strain insulator at one end of the span.

This test shows the different deflections of insulators and sags, and gives an idea of the decreasing effect in the spans out along the line. Curves in Figs. 7, 8 and 9 apply to this test.

Third Test. All tension on the middle cable in spans 2 and 4

affecting span 3 was taken out, and the insulators on poles 3 and 4 were allowed to swing towards span 3.

This test shows the great increase in sag due to swing of the insulator alone, and a further increase of sag (but of comparatively small amount in proportion) due to the elastic properties of the wire.

Reference to curves in Figs. 10, 11 and 12 will show the results.

Fourth Test. Strain clamps were placed on the ends of the

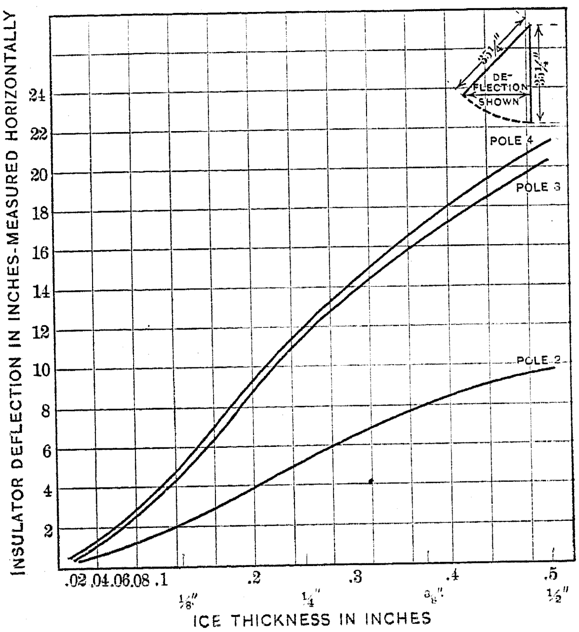


FIG. 5—FIRST TEST

Middle wire in span 3 loaded. Curves show deflections of insulators holding middle wire.

middle cable in span 3, and therefore the various loadings applied showed the effect of the elastic properties of the cable alone.

Fig. 13 covers this test.

The results of the above tests showed that for this particular tower line, its combination length of spans, size and material of wire, and the character of weather conditions, called for a change in arrangement of conductors from the vertical plane. Therefore the point of attachment to the crossarm of the top

insulator was moved in towards the tower, the middle cross-arm lengthened and the attachment to the bottom arm left as originally constructed.

The conductors were then no longer in a vertical plane, and one winter's experience has shown no short circuit, though the horizontal clearance between vertical planes through the cables is not as much as would be provided on a new tower.

The conclusions to be drawn from this experience are more

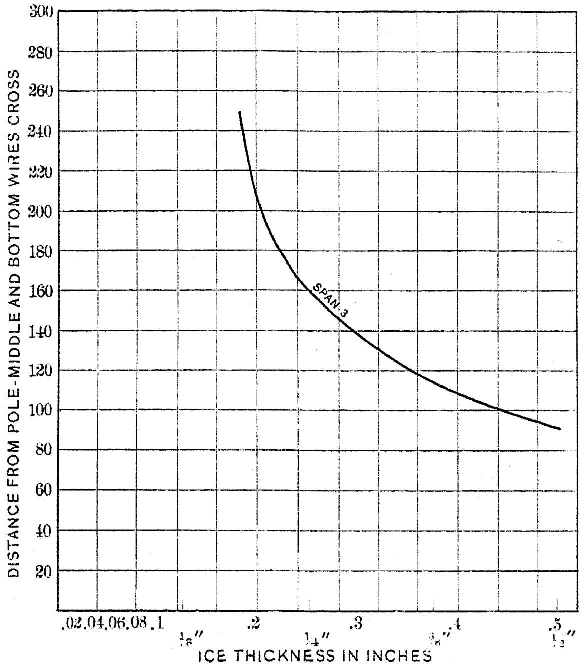


FIG. 6—FIRST TEST
Middle wire in span 3 loaded. Bottom wire unloaded.

than simply the advisability of changing wires arranged in a vertical plane, since it is also a fact that with long spans and wires arranged in a horizontal plane, although the conductors will no longer cause short circuits, they will nevertheless sag down within unsafe distances of the ground.

Therefore, in designing a transmission line with suspension insulators, a more careful examination should be made of *all* the mechanical features of the construction under consideration.

It is obvious that the length of span should be adjusted to

the material and size of the conductor, to the weather conditions experienced or expected, the voltage of the line, and therefore the length of the suspension insulators. The question of right of way also must be considered, and the final test of the allowable amount of expenditure for the service to be performed by the line, will set the limits of construction.

Since a conductor should be strung with due regard to the maximum stress at low temperature, ice and wind loading (as estimated from records in the district where a line is to be

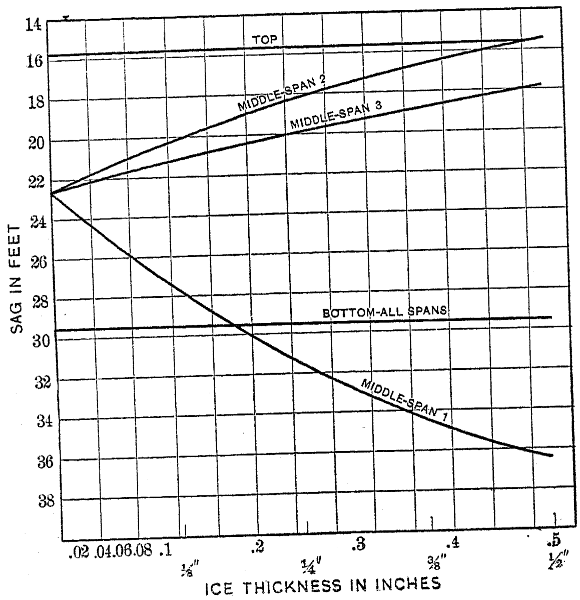


FIG. 7—SECOND TEST
Middle wire in span 1 loaded.

constructed), it is plainly desirable that a conductor having the highest elastic limit should be selected.

If the electrical characteristics of high strength steel cable and its price made it worthy of consideration, it should be obvious that the steel cable could be strung in such a flat catenary that the loading of ice on one span with adjacent spans unloaded, would not cause very much transference of sag to the loaded span.

The use of such cable would of course require strain insulators at suitable points to maintain its position, especially at places

where change of grade occurred. The use of steel-cored aluminum or steel-cored copper, or of bimetallic cable composed of steel wires surrounded by copper, and hard drawn copper of the highest strength, can all be considered with reference to the length of span and sag when using suspension insulators.

The tests described show the great influence of length of insulator on the increased sag, and it appears that notwith-

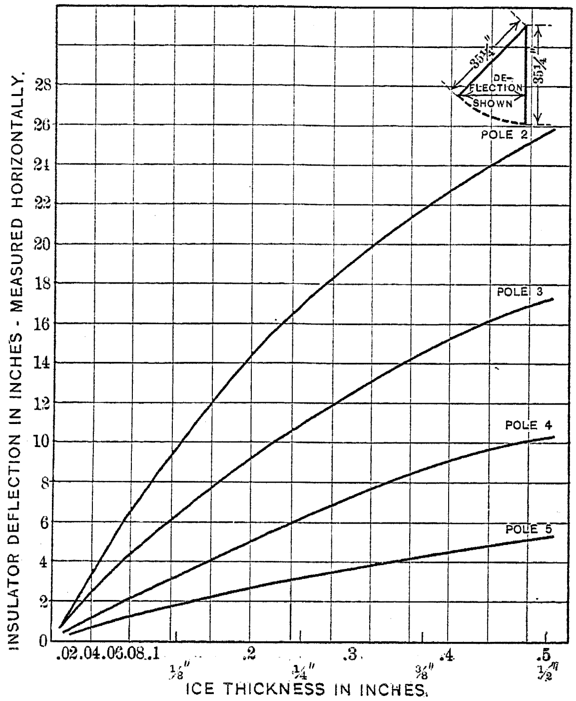


FIG. 8—SECOND TEST

Middle wire in span 1 loaded. Curves show deflections of insulators holding middle wire.

standing the great advance made by insulator designers in bringing out the suspension type, definite endeavor should be made to shorten up the insulators as much as is practical, especially for high-voltage work, where long length of insulators and small light-weight conductors both tend to aggravate the effects shown in this paper.

One of the most difficult features to consider is that of weather

effects, especially the simultaneous conditions of low temperature, ice or sleet and wind. This is especially true in the West, where Government weather stations are not located near each other, and where the district to be traversed by a line is sparsely settled. There is then no fund of information on which to draw, and the general judgment of the engineer must be relied upon. The engineer should inform himself on the method of formation of sleet and frost, and as to the general topography of the surrounding district, and the source and direction of

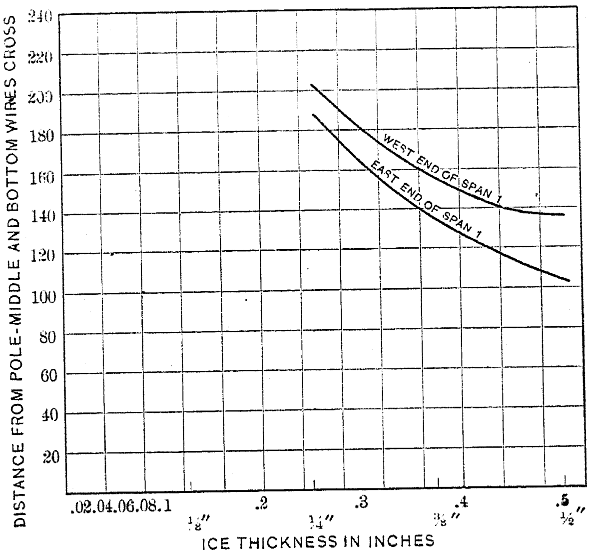


FIG. 9—SECOND TEST
Middle wire in span 1 loaded. Bottom wire unloaded.

travel of the storms which will reach the line. Such general information can usually be secured.

In the case of the tower line described above, it can be stated that the line runs in a northwesterly direction from Spokane, and is at an average altitude of about 2000 feet (610 m.) above sea level.

Two specific kinds of trouble were experienced, one due to very heavy hoar frost being deposited by fogs from the Columbia River valley to the southwest, and which melted rapidly as the fog lifted and the sun came out, this melting usually occurring on the different spans at different rates.

The other weather effect was the deposition of wet snow driven by a hard wind from the southwest, approximately at right angles to the line. This wet snow load sometimes froze solid and was of unusual shape. The outside contour of the snow was approximately that of a flattened ellipse with the conductor at one focus, the snow adhering and piling up on the windward side of the conductor, but not on top. It has

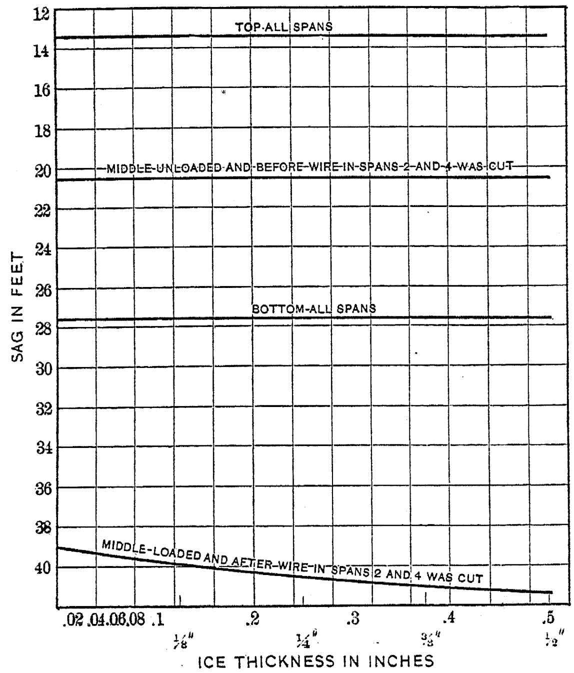


FIG. 10—THIRD TEST

All tension in the middle wire in spans 2 and 4 was taken out and the insulators on the middle wire in span 3 allowed to swing toward span 3. Span 3 was then loaded. This was equivalent to cutting the wires in spans 2 and 4 near the insulators at poles 3 and 4.

also been found that heavy fogs would deposit in the same manner.

Authentic reports on ice loading of telephone and high-tension wires in this district show that the dimensions of such deposits have been about 1½ inches (3.81 cm.) in the vertical plane by 3½ inches (8.9 cm.) in the horizontal, on a No. 9 B.w.g telephone wire, the weight per foot (0.3048 m.) of deposit being 0.8 lb. (0.363 kg.), all by actual measurement.

In another case of a No. 0 aluminum cable, the dimensions of the deposit were $1\frac{3}{4}$ inches (4.45 cm.) thick by 6 inches long (15.2 cm.).

The outside surface of such deposits is very rough and it is useless to use the ordinary formula in calculating wind pressure, as the surface is more nearly that of a plane than a round smooth wire or stranded conductor.

In the cases of wet snow deposits, a high wind usually ac-

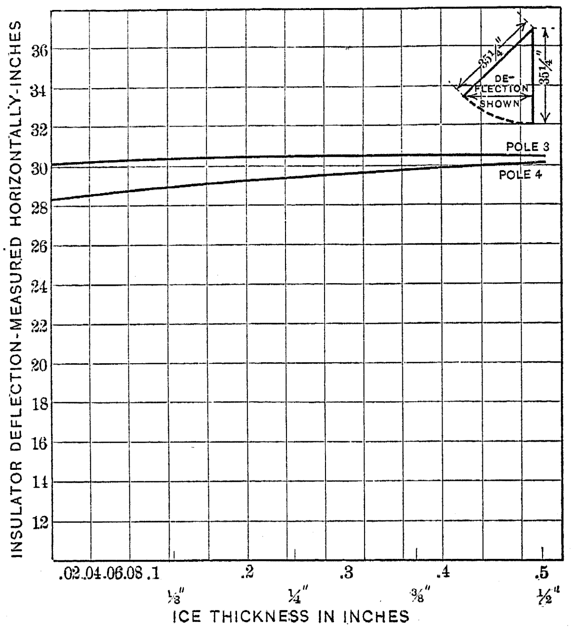


FIG. 11—THIRD TEST

Curves show deflections of insulators holding middle wire in span 3

companied the snow, with the temperature around the freezing point.

Financial considerations will generally limit the reduction of length of span, but a carefully made total cost curve of different tower spacings will frequently show that the cost over a wide range of spacing is very nearly constant. This is especially true if the proper allowances are made on cost of towers, etc., for the different spacings. In such cases, some consideration should be given to the smaller maintenance expense and

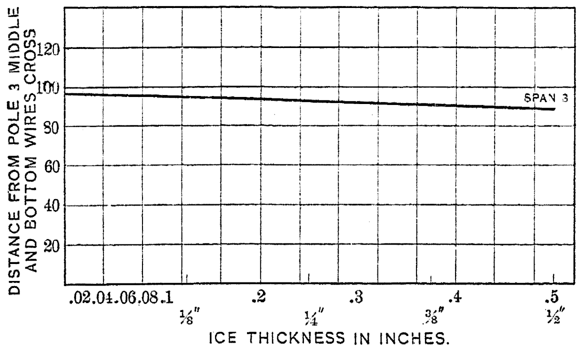


FIG. 12—THIRD TEST

Bottom wire unloaded.

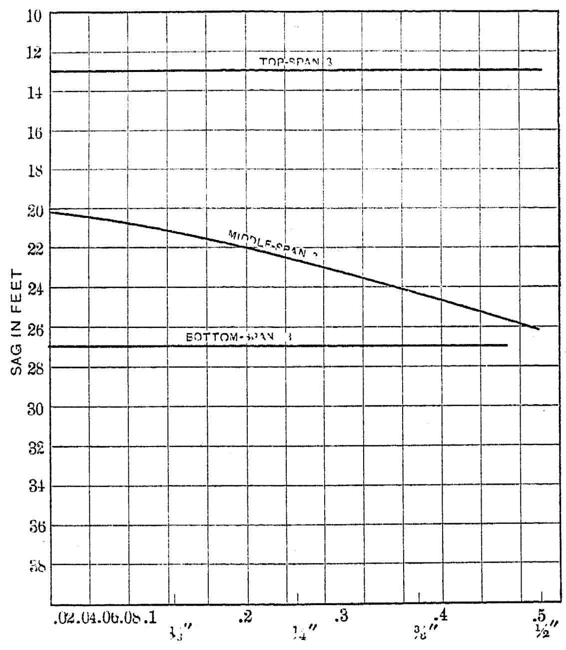


FIG. 13—FOURTH TEST

Strain clamps were placed on the middle wire in span 3 and the wire fastened solidly to the crossarms. Span 3 was then loaded. This was equivalent to a line with strain insulators at every tower.

more reliable operation of the shorter spans, and the final tower spacing chosen with all these facts in mind.

It is hoped that this paper will not be construed as condemning long spans or suspension insulators, for such is not the intention, but it is desired to show that transmission lines should be built with due regard to *all* the stresses which will develop in the supporting structures and conductors, if good service and low maintenance and operating costs are desired.

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 10, 1913.

MOUNTAIN RAILWAY ELECTRIFICATION
A Study of the Tehachapi Pass

BY ALLEN H. BABCOCK

During the past ten years the Southern Pacific Company has investigated the question of electrification of its three outlets from the central valleys of California, north, over the Siskiyou, east, over the Sierra, and south, over the Tehachapi. The earlier reports, inspired directly or indirectly by manufacturers as a part of their propaganda program, were favorable to electrification. The railway company then began studies of the subject, independently. The conclusions of its officers were unanimously opposed to electrification, by reason of the financial results to be anticipated; however, some of its lines have been electrified, and other electric lines have been acquired for good reasons.

Lately there has been a constant and persistent pressure put upon the company officials, by both power companies and consulting engineers, to reconsider decisions adverse to electrification, decisions that were made after patient and thorough study, and in the face of the fact that to be connected with any such important engineering work as these installations would be, would fire the professional imagination of any engineer worthy of the name. Just how much of this agitation has been due to the application of general statements regarding the benefits to be secured by electrification, to the particular problems presented by west coast mountain railroading, is hardly susceptible of direct determination. It is possible, however, that much of it is due to the effect that such hypothetical studies and papers as have been published recently, have produced upon executives, who, however skilled they may be in their specialties, only in

rare instances are sufficiently experienced technically to be capable of forming independent opinions on engineering matters. It is a fact that reports adverse to electrification in the hands of these same executives, often cause disappointment and sometimes arouse criticism.

Here, then, are two opposing parties; the one with things to sell, (apparatus, power, engineering skill), the other with a service to be maintained, at decreased cost if possible, but maintained at any cost it must be: the first reports favorably upon projects that the second considers unfavorably with equal positiveness. Some things must be unknown to both. Either the radicals have not all the facts upon which to work, or the conservatives cannot interpret their facts correctly.

Words have been multiplied with reference to the subject until aspiring authors well may pause before adding fuel, not to say fat to the fire; but it is with these thoughts in mind this paper is written, not with the intent to offer anything original in the study of such problems but to give the facts of a typical west coast mountain railroad district and their interpretation as seen by one whose reports heretofore have been responsible for many adverse decisions in such matters.

It is not intended to be the final word on the subject of electrification of this district, but it is the result of a study recently made to determine whether there was such a reasonable chance for profitable electrification as would warrant a very considerable expense in time and money, such as was incurred a few years ago in an exhaustive and final study of the Sierra problem, for example.

If through the facts given herein, and in the discussion thereof, a better mutual understanding will be reached, its purposes will have been served.

Physical Characteristics

West Slope, Bakersfield to Summit........................49½ miles

Vertical rise..3764 ft.

Average grade..1.44 per cent

Average curvature equal to a constant 3 deg. curve.

Total curvature, 7944 deg., of which 6969 deg. are between Caliente and Summit (27.2 mi.). The loop curve has a total curvature of 566 deg. 33 min. 12 sec.

East Slope, Mojave to Summit..........................18.3 miles

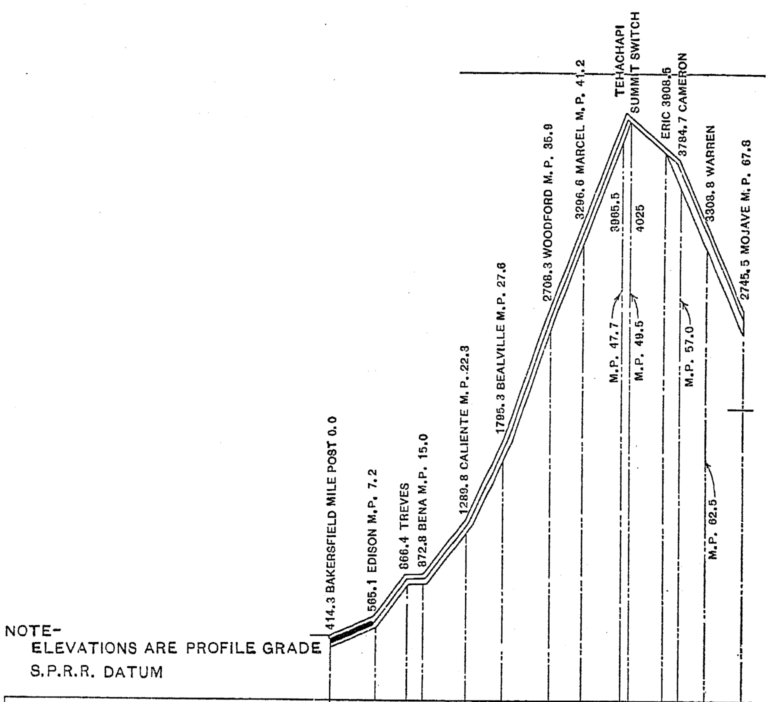
Vertical rise..1285 ft.

Average grade..1.33 per cent

Average curvature (as above)...........................0.79 deg.

Total curvature..765 deg.

The ruling grade on each slope is 2.2 per cent, but these grades are not compensated for curvature so that in effect the ruling grade is 2.4 per cent. The maximum grades are long enough to fix the weight and power of the locomotives. The average distance between sidings is three miles, approximately.



MAXIMUM GRADE (FEET PER MILE)		105.6	116.16	116.16
CURVED LINE (MILES)	FROM 0° TO 6° INCL.	11.34		6.44
	" 6°01 " 8° "	2.38		
	" 8°01 " 10° "	7.67	2.63 OF 10°01 & OVER	
TOTAL ASCENTS EAST (FEET)		3686.885		5.5
" " WEST (")		76.885		1285.03
TOTAL CURVATURE		7944°		765°

FIG. 1—CONDENSED PROFILE, TEHACHAPI PASS

In determining energy consumption of trains moving over the mountain the actual characteristics of the line were used, (see Appendix K), but in determining load diagrams and substation spacings and capacity, the following close approximations were

made to take care of the ruling grade, curves, etc. (For their application see Appendix A.)

Section	Miles	Average grade
Bakersfield to Edison	7.2	0.5 per cent
Edison to Caliente	15.1	1.5 " "
Caliente to Summit	27.2	2.4 " "
Mojave to Cameron	10.8	2.4 " "
Cameron to Summit	7.5	0.75 " "

The average freight train, eastbound, weighs 2000 tons, exclusive of locomotives. Four consolidation or decapod type locomotives, or their equivalent in Mallet compounds, are used to haul this train from Bakersfield to Summit. From Summit to Mojave one locomotive is used for supplying air for brake purposes, etc., and the other three return deadhead to Bakersfield. The westbound freight trains are lighter than the eastbound on account of the fact that much of the western movement consists of empty cars. The normal weight is 1250 tons, hauled by three consolidation locomotives, or their equivalent in Mallets; or a 1500-ton train operated by three consolidation or decapod locomotives, or their equivalent in Mallets. The helper engines cut out at Summit and return light to Mojave.

In order to provide a flexible unit it was proposed to use an electric locomotive, capable of handling a train unit of 500 tons, as many per train to be used as the weight of the train requires. The weight of the electric locomotives is assumed at 100 tons.

Passenger train weights vary from 250 tons to 600 tons, for which a single passenger locomotive weighing 150 tons was provided. A maximum freight train movement over the mountain recently consisted of twelve full-size freight trains, eastbound, and eight full-size freight trains, westbound, in addition to the normal passenger movement, which is seven regular trains each way per day, with occasional extras and second sections.

The track, particularly on the west slope, is laid for the greater part of the distance in rough country, in fact between mile posts 326 and 361 all the track, with the exception of a short stretch near Caliente, is in cuts or on fills. It may be said generally that at least half the track is laid in conditions where any overhead contact system would require, necessarily, very expensive steel pole or bridge construction. In addition to the above, there are 18 tunnels, in none of which the vertical clearance is more than 18½ ft., and 60 per cent of their total length is on 10-deg. curves. A detailed list of tunnels is given in Appendix L-1.

Experience with similar earlier reports has shown that, in general, there is little difference in total first cost and annual operating costs, whether an overhead system or the third rail system be considered. A double overhead contact system gives maximum first cost and operating costs for contact system, and minimum weights, costs and maintenance of locomotives; a single overhead contact system gives high first cost and operating costs for contact system, with maximum weights and maintenance of locomotives; the third rail gives high first cost and minimum operating cost of contact system, medium locomotive weights and first costs, with minimum operating costs, but the total costs are brought up to the level of the others by reason of the necessary substation apparatus and attendance. A choice of systems therefore is to be made only after an exhaustive study of all the local conditions.

In a preliminary study, as this is, it matters little what particular system of propulsion is chosen, upon which to base the estimates. For the purposes of this discussion a 2400-volt continuous-current, third-rail contact system was selected for the main line, with an overhead contact system in yards and terminals, at Kern, Bakersfield and Mojave.

In the following, the First Costs are based on the present traffic as shown by the train dispatcher's sheets; the Annual Operating Costs are taken from the reports of the fiscal year ending June 30, 1912, for steam operation, while the same traffic and reports are used, as far as they apply, in estimating the costs for electric operation.

FIRST COSTS

Substations,	Appendix A	$1,610,000
Generating station,	" B	1,760,000
Transmission system,	" C	430,050
Contact system (yards)	" C	155,250
" " (line),	" A	825,000
Bonding,	" A	122,300
Block signals,	" D	175,000
Shops and inspection shed,	" E	10,000
Electric locomotives,	" F	2,085,000
Total		$7,172,600
Credit by steam locomotives released for service on other divisions, Appendix G		1,464,900
Net first cost		$5,707,700

Annual Operating Costs (Steam-generated power)		Steam	Electric
Substation labor and supplies,	Appendix A.....		$59,700
Power house labor and supplies	" B......		84,780
Transmission and contact system maintenance,	" C.....		36,576
Maintenance of way as affected by locomotives,	" H.....	$126,890	83,285
Locomotive repairs,	" I......	270,990	70,701
Loco. enginemen, (passenger),	" J.....	48,300	29,100
Fuel,	" K.....	240,852	100,530
		$687,032	$464,672
Bond interest at 4½ per cent on net first cost....			256,847
Totals..................................		$687,032	$721,519

Net loss, $34,487

In the above no account is taken of items not affected by character of motive power: freight enginemen, and all train crew wages, repairs to cars and maintenance of way as affected by cars—for example.

The net loss under proposed electric operation is so small that it might be wiped out by a reasonably small change in the assumptions; in fact, at this stage of similar investigations often there is a temptation to search for opportunities to change this, or to modify that, as the necessities of the case demand. This important fact should be borne in mind, however, that in the foregoing no account is taken of taxes and depreciation, both of which must be paid, some time, by some one, to the extent of at least 5 per cent of the net investment, which increases the net loss by approximately $285,000 per year.

It may be asked, why is depreciation not taken into account in the usual manner? The answer is, since there is a loss, or at least no profit shown, and since to add depreciation would be to make a bad matter only worse, nothing is to be gained by entering into the academic discussions that inevitably follow the opening of a subject concerning which opinions reasonably may differ as widely as on this much disputed particular.

But power may be purchased, as is often suggested by those with power for sale, hence it is proper to determine at what rate this power may be purchased and come out even as compared with operation by steam-generated power. Obviously any rate less than this will be profitable.

With purchased power, the total investment will be diminished

by the costs of 20 miles of transmission line and of the generating station, it being assumed that power will be delivered at some one point on the right-of-way, whereas local conditions located the steam station 20 miles off the right-of-way (see Appendix B).

The net first cost was....................................		$5,707,700
Transmission line, Appendix C...............	$120,000	
Generating station " B...............	1,760,000	1,880,000
Leaving a net investment with power purchased.........		$3,827,700

ANNUAL OPERATING COSTS
(Power purchased)

		Steam	Electric
Substation labor and supplies,	Appendix A....		$59,700
Transmission and contact systems maintenance,	" C....		35,576
Maintenance of way as affected by locomotives,	" H....	$126,890	83,285
Locomotive repairs,	" I.....	270,990	70,701
Loco. enginemen, (passenger),	" J....	48,300	29,100
Fuel,	" K....	240,852	
		$687,032	$278,362
Bond interest at 4½ per cent on net first cost....			172,247
Totals..................................		$687,032	$450,609

The difference, $236,423, should be decreased by $191,385, (the approximate tax and depreciation rate of 5 per cent on the net investment of $3,827,700), and there is left the wholly inadequate sum of $45,038 with which to purchase 53,000,000 kw-hr. at a load factor of about 20 per cent; with no profit to show for an investment of nearly $4,000,000.

For the sake of the argument let the depreciation be neglected and let it be considered that $236,423 are available for the purchase of power under the operating conditions of the service. At any time there may be four passenger and four freight trains pulling up hill simultaneously, taking a total of 32,720 kw. alternating-current input to the line. This is not the maximum number of trains that is on the mountain regularly, but represents only those taking power. A slight derangement of schedules, or an extra freight movement, citrus fruits or oil, or a blockade, for example, will cause congestion beyond any possibility of estimating. This traffic must be handled as circumstances require. It cannot be spaced conveniently for power demands, as many engineers and power men have suggested, but the term-

inal yards must be cleared as the cars accumulate. Is there any power company in the west coast country, or even beyond the reach of such a natural power source as Niagara, that would care to undertake such a load for any such yearly return as that named in this paragraph? It would net about $4\frac{1}{2}$ mills; a rate that neither the purchaser nor the seller could afford to consider.

In the face of the foregoing it is difficult to see how any recommendation in favor of electrification can be made, if the opinion is based on the direct financial profit to be realized; in other words, this case is merely another example of the fact often noted, that in the great majority of cases the profits from electrification must be realized indirectly rather than directly,—increased track capacity, postponing second- or double-tracking, or the like.

It may be urged that a larger district would make a better showing. In this connection it may be noted that the line from Bakersfield to Summit is almost identical with half of the line assumed in Mr. Hobart's paper on 2400-*Volt Railway Electrification.** On each side of the summit Mr. Hobart's assumed line is 3800 ft. rise in 48 miles with the ruling grade of 2.2 per cent, while the west slope of the Tehachapi is $49\frac{1}{2}$ miles, rise of 3764 ft. and a ruling grade of 2.4 per cent. Also Mr. Hobart assumes freight train weight on heavy days of 1800 tons as against 2000 tons on the Tehachapi. Furthermore, the Sierra study covered a district more than double the length of the Tehachapi, and the result was the same.

In the various appendices will be found complete details of all the elements of the investigation, as noted by the cross references given after the various items of the tabulations herein.

Acknowledgments are hereby made to Mr. G. W. Welsh and Mr. F. E. Geibel, both assistant engineers in the electrical engineer's office, Southern Pacific Company, for assistance in the preparation of this paper. The former made a thoroughly painstaking study of the problem as a whole, and to the latter is due the novel method of determination of substation spacing and capacity as detailed in Appendix A.

APPENDIX A

SUBSTATIONS

Substation Spacing and Heating Loads. It is not the purpose here to go into a theoretical discussion of the economical spacing

*See p. 1149, this volume.

of substations, balancing off the losses and fixed charges of the distributing system against the losses and fixed and operating charges of the substations. Any such discussion requires the lengthy consideration of various operating conditions which seldom, if ever, are obtained in practise; hence the determination leads nowhere.

The following is simply a brief description of a very convenient and quick method of determining the feeder and substation layout in preliminary studies of the electrification of mountain divisions of steam railroads. The method was developed by Mr. F. E. Geibel, assistant engineer, Southern Pacific Company, in the original study of the problem.

The conditions, as set forth in the general study, require an average train speed over the electrified section. It is therefore necessary to maintain an average voltage over the sections between substations. Formulas for the average volts drop over the section were deduced as follows:

Let L = distance in miles between substations.
I = current per train in amperes.
R = resistance of distributing system in ohms per mile of circuit.
A = distance in miles between first and second trains.
B = distance in miles between second and third trains.
V = volts at substation.
E = instantaneous volt drop on line.
D = average volts drop over section between substations.
X = distance in miles between first train and a substation.

Considering first only one train between substations:

$\left(\frac{L-X}{L}\right) I$ = current drawn from one substation.

XR = total resistance to same substation.

Therefore $E = \frac{RI}{L}(XL - X^2)$

$$\text{but } D = \frac{\sum_0^L E}{L} = \frac{RI}{L^2}\int_0^L (XL - X^2)\, dX$$

$$= \frac{1}{6} R I L = \text{average volts drop.}$$

Similarly, formulas for two and three trains in a section were deduced, for average drop as follows:

One train between substations, $D = \frac{1}{6} R I L$

Two trains " " $D = \frac{1}{6} R I \left(2L - \frac{3A^2}{L} \right)$

Three " " " $D = \frac{1}{6} R I \left[3L - \frac{2(2A + B)^2}{L} \right]$

If the trains are following at equal distances then $A = B$ and the last formula becomes

$$D = \frac{1}{6} R I \left[3L - \frac{2(3A)^2}{L} \right]$$

The loads on the substations were plotted graphically for several substation spacings up to twenty-five miles, and the heating loads were computed for each spacing. It was found, however, that the heating load varied approximately as follows:

Total heating $= 2 \left(\frac{L}{A+B} \right) VI$ for trains alternately A and B miles apart, when the distance between substations is equal to or greater than the greater spacing between the trains. For trains of equal distance apart, total heating $= 2 \left(\frac{L}{2A} \right) VI$. VI is the amperes per train multiplied by the substation voltage.

It is to be noted here that all of the above expressions apply only to direct-current systems and cannot be used on single-phase systems without complication. It is, also, to be noted that the formulas are deduced assuming trains running in one direction only, as, on the grades considered, the trains coming down grade do not draw a running current but only a small current for control purposes.

In applying the formulas to the problem in hand the following assumptions were made:

2000-ton trains with four 100-ton locomotives per train.

Trains 15 miles per hour, spaced alternately 5 and 10 miles apart.

Locomotive efficiency 90 per cent. Train resistance 6 lb. per ton.

Substation voltage 2400. Train voltage 2100 average.

In Fig. 2 will be found curves showing the total conductivity, in terms of total million circular mils of copper equally divided between positive and negative circuits, required to give the average voltage over the section for various grades. These curves were plotted from the formulas given above. With substation spacings up to 8.65 miles, the average drop is greater with one

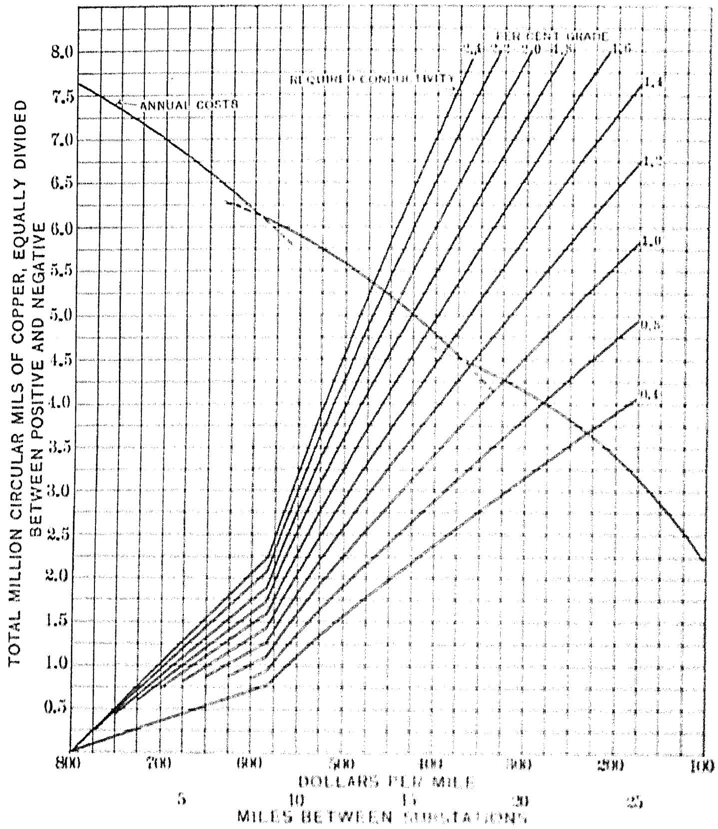


FIG. 2—CONTACT SYSTEM

train in the section, and between 8.65 miles and 26.9 miles the average drop is greater with two trains in the section. Hence the break in the curves at 8.65 miles.

There is also plotted in Fig. 2 a curve giving the annual costs per mile on a contact system of the required conductivity. A contact rail system was considered with no positive feeders but 75-lb. old rail as negative feeder. The annual cost curve

shows three distinct sections, namely: the lower section, no negative feeder; the middle section, one 75-lb. rail negative feeder; and the upper section, two 75-lb. rail negative feeders. As worked out, however, the system required no negative feeder. From Fig. 2, it is seen that the annual cost per mile on the con-

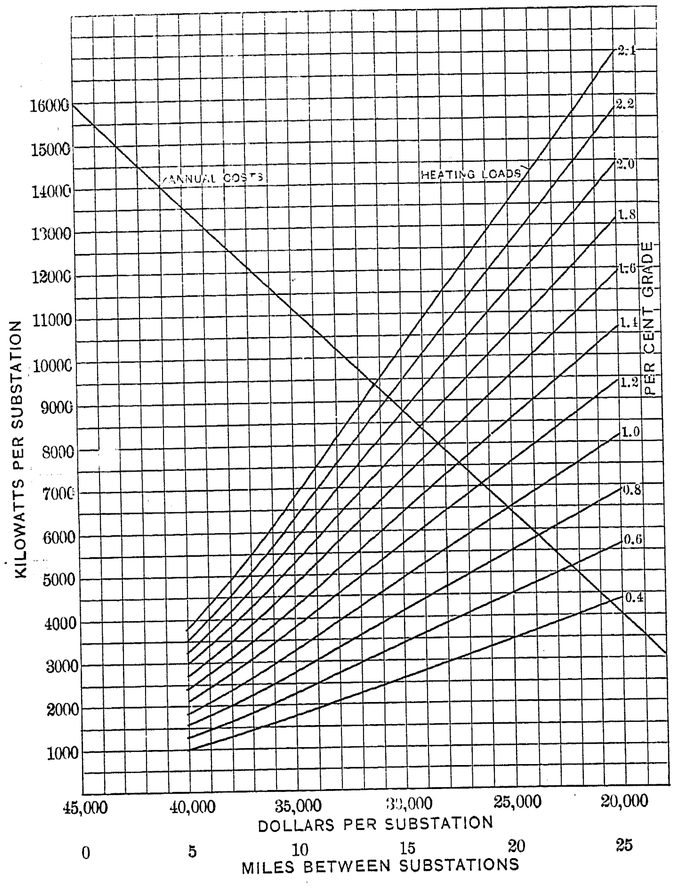


FIG. 3—SUBSTATIONS

tact system for any given substation spacing and grade can be read directly.

Similarly from Fig. 3 the heating loads on substations for any given spacing and grade may be read off, or, if referred to the annual cost curve, the annual cost per substation is given. This

latter value divided by the spacing gives the substation annual costs per mile.

The above annual costs were taken at various substation spacings on several given grades and the results, the total annual costs per mile, were plotted in Fig. 4. This gives a series of

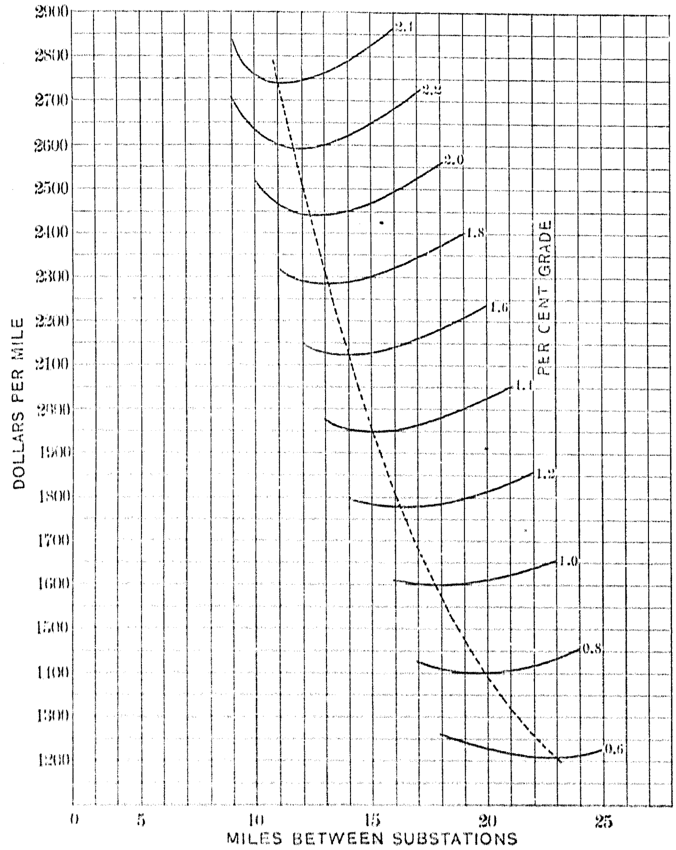


Fig. 4—Total Annual Costs

curves, the minimum of each being the economical substation spacing on the given grade. These results were transferred to Fig. 5 which shows, for any given grade, the economical spacing, the heating load on substation and the size of contact rail required.

As stated in the report, the track district under study was divided into several sections of average grades. By applying

the latter curve, therefore, to these sections the spacing and heating loads of the substations are easily determined.

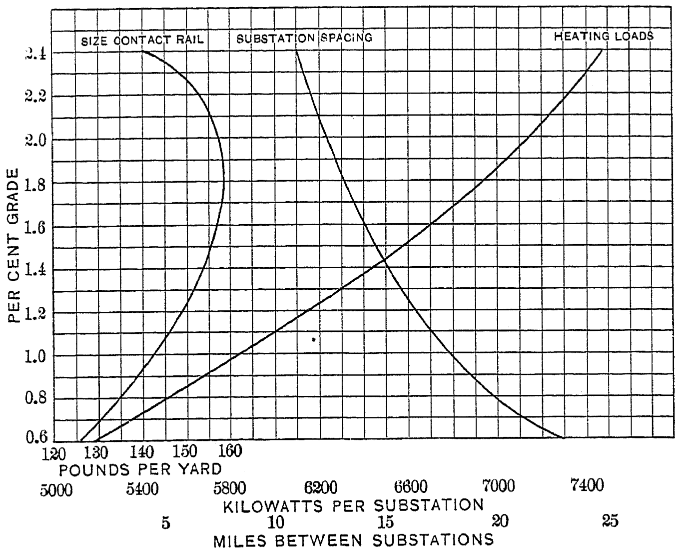


FIG. 5—ECONOMICAL SUBSTATION SPACING

After making the proper allowance for yard switching and stub ends, the following substations were located:

No. substation	Spacing	Heating load	Installed capacity
1	5 miles from Bakersfield	4900 kw.	three 2000-kw. units
2	13.5 mi.	6500 "	four 2000 " "
3	11.6 "	7200 "	four 2000 " "
4	10.5 "	7000 "	four 2000 " "
5	10.5 "	6600 "	four 2000 " "
6	13 "	6900 "	four 2000 " "
	3.7 mi. to Mojave		

SUBSTATIONS

The unit first costs used are as follows:

$35 per installed kw.

The above is based on a recent west coast installation, corrected for 2400-volt apparatus.

OPERATING COSTS

1 *Station*—6000 kw. capacity. Labor, 3 shifts,
2 men each, $1300 and $1000............. $6900
Repairs and supplies..................... 2200 $9100 $9,100

5 *Stations*—8000 kw. capacity. Labor, 3 shifts, 2 men each, $1300 and $1000	$6900		
Repairs and Supplies	2500		
		$9400	$47,000
2 Substation foremen at $1800			3,600
			$59,700

CONTACT RAIL, 2400 VOLTS

The larger part of the grade being either 2.4 per cent or under 1 per cent, a 140-lb. contact rail was required for the main line and 75-lb. for sidings.

MAIN LINE

Material:		
110 tons special 140-lb. contact rail at $33.00 per ton		$3630.00
Freight thereon at $13.50 per ton		1485.00
176 pairs splice plates delivered	$88.00	
Bolts and nuts	12.00	
704 bonds at 74c	521.00	
480 insulators, brackets and felt delivered	480.00	
Paint	20.00	
10 inclines at $7.50	75.00	
5 jumpers at $100.00	500.00	
Anchoring, modified ins. caps, extra 10c x 176	17.60	
Substation connections	35.00	
960 long ties excess cost at 50c	480.00	
960 brackets for protection at 50c	480.00	
Lumber for protection	500.00	
Bolts, screws and fittings	80.00	
	$3288.60	
Extras 5 per cent	164.40	
	$3453.00	
Store charges 6 per cent	207.00	$3660.00
Labor:		
Delivering rail 110 tons at $1.50	$165.00	
Installing insulators 480 at $.10	48.00	
" protection brackets at $.10	96.00	
" rail	200.00	
" bonds at $.30 ea	211.20	
" protection	400.00	
Painting	100.00	
Work train	100.00	
	$1320.20	
Extras 10 per cent	132.00	$1452.20
		$10,227.20

Say $10,225.00 per mile

SIDINGS

Material:		
59 tons special 75-lb. contact rail at $46.50 del.........		$2740.00
352 bonds at 60c..........................	$211.20	
Other material..........................	2560.80	
	$2772.00	
Extras 5 per cent......................	138.60	
	$2910.60	
Store charges 6 per cent................	174.60	$3085.20
Labor:		
Delivery of rail 59 tons at $1.50............	$93.50	
Installing bonds at 30c....................	105.60	
" insulators......................	48.00	
" protection brackets..............	96.00	
" rail...........................	100.00	
" protection.....................	400.00	
Painting................................	100.00	
Work train.............................	100.00	
	$1043.10	
Extras 10 per cent.....	104.30	$1147.40
		$6972.60
Say...........		$7000.00

The above is based on Pennsylvania R.R. type of third rail with protection installed on both sides. Cost of rail is based on New York Central cost of special rail plus freight charges. Cost of specialties is taken from quotations. Labor is according to west coast practise.

MAIN LINE BONDING

Two 10-in., 450,000-cir. mil bonds per joint.

Bonds..................................	$570.00	
Cross bonds............................	75.00	
Labor..................................	375.00	
	$1020.00	
Extras................................	102.00	$1122.00

SIDINGS AND YARD TRACK BONDING

Two 4/0 bonds per joint.

Bonds..................................	$320.00	
Cross bonds............................	100.00	
Labor..................................	400.00	
	$820.00	
Extras 10 per cent.....................	80.00	$900.00

The above is based on the actual cost of bonding in an installation recently made in the vicinity of San Francisco. The fact that the track would be bonded under heavy traffic should not be overlooked.

TOTAL FIRST COSTS

Substation and Distribution

Substation		
46,000 kw. at $35		$1,610,000
Contact rail		
65.84 mi. main line at $10,225	$673,000	
21.60 mi. sidings at $7000	152,000	
		825,000
Bonding		
65.84 mi. main line at $1120	$73,800	
21.60 mi. sidings at $900	19,440	
32.29 mi. yard tracks at $900	29,060	122,300
		$2,557,300

Annual Costs

For the reason that one organization should maintain all transmission and distribution system, the annual costs of maintenance and repair for contact system are to be found under Transmission Line Costs, Appendix C.

APPENDIX B

Generating Station

Two principal considerations fixed the generating station at a distance from the track: fuel and water.

Twenty miles off the right-of-way from a point 6 miles east of Bakersfield is located a large oil field from which the company obtains much of the fuel oil used in its locomotives. Plenty of water for condensing purposes is obtainable near by. The annual charges on a transmission line under these conditions do not impose so heavy a burden on the operating costs as would the delivery of oil at the right-of-way; besides, to develop sufficient water along the track would cost a great deal. For these reasons the generating station was located in the oil fields on fairly level land where excavating costs were reasonable and on soil sufficiently firm for ordinary foundations.

The load curve, Fig. 6, indicates that a three-unit station is desirable, two units of which would carry the load ordinarily, with one as a spare. A study of the load curve and train diagram fixed the maximum capacity of the units at 18,000 kw. at the two-hour overload rating—an economical size in first cost and in annual operating costs. The point of maximum economy without auxiliary nozzles is in the neighborhood of 10,000 kw., and the hand-operated nozzle will enable the machine to carry

Sidings

Material:		
59 tons special 75-lb. contact rail at $46.50 del.		$2740.00
352 bonds at 60c.	$211.20	
Other material	2560.80	
	$2772.00	
Extras 5 per cent	138.60	
	$2910.60	
Store charges 6 per cent	174.60	$3085.20
Labor:		
Delivery of rail 59 tons at $1.50	$93.50	
Installing bonds at 30c.	105.60	
" insulators	48.00	
" protection brackets	96.00	
" rail	100.00	
" protection	400.00	
Painting	100.00	
Work train	100.00	
	$1043.10	
Extras 10 per cent	104.30	$1147.40
		$6972.60
Say		$7000.00

The above is based on Pennsylvania R.R. type of third rail with protection installed on both sides. Cost of rail is based on New York Central cost of special rail plus freight charges. Cost of specialties is taken from quotations. Labor is according to west coast practise.

Main Line Bonding

Two 10-in., 450,000-cir. mil bonds per joint.

Bonds	$570.00	
Cross bonds	75.00	
Labor	375.00	
	$1020.00	
Extras	102.00	$1122.00

Sidings and Yard Track Bonding

Two 4/0 bonds per joint.

Bonds	$320.00	
Cross bonds	100.00	
Labor	400.00	
	$820.00	
Extras 10 per cent	80.00	$900.00

The above is based on the actual cost of bonding in an installation recently made in the vicinity of San Francisco. The fact that the track would be bonded under heavy traffic should not be overlooked.

TOTAL FIRST COSTS

Substation and Distribution

Substation		
46,000 kw. at $35		$1,610,000
Contact rail		
65.84 mi. main line at $10,225	$673,000	
21.60 mi. sidings at $7000	152,000	
		825,000
Bonding		
65.84 mi. main line at $1120	$73,800	
21.60 mi. sidings at $900	19,440	
32.29 mi. yard tracks at $900	29,060	122,300
		$2,557,300

Annual Costs

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APPENDIX B

Generating Station

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The load curve, Fig. 6, indicates that a three-unit station is desirable, two units of which would carry the load ordinarily, with one as a spare. A study of the load curve and train diagram fixed the maximum capacity of the units at 18,000 kw. at the two-hour overload rating—an economical size in first cost and in annual operating costs. The point of maximum economy without auxiliary nozzles is in the neighborhood of 10,000 kw., and the hand-operated nozzle will enable the machine to carry

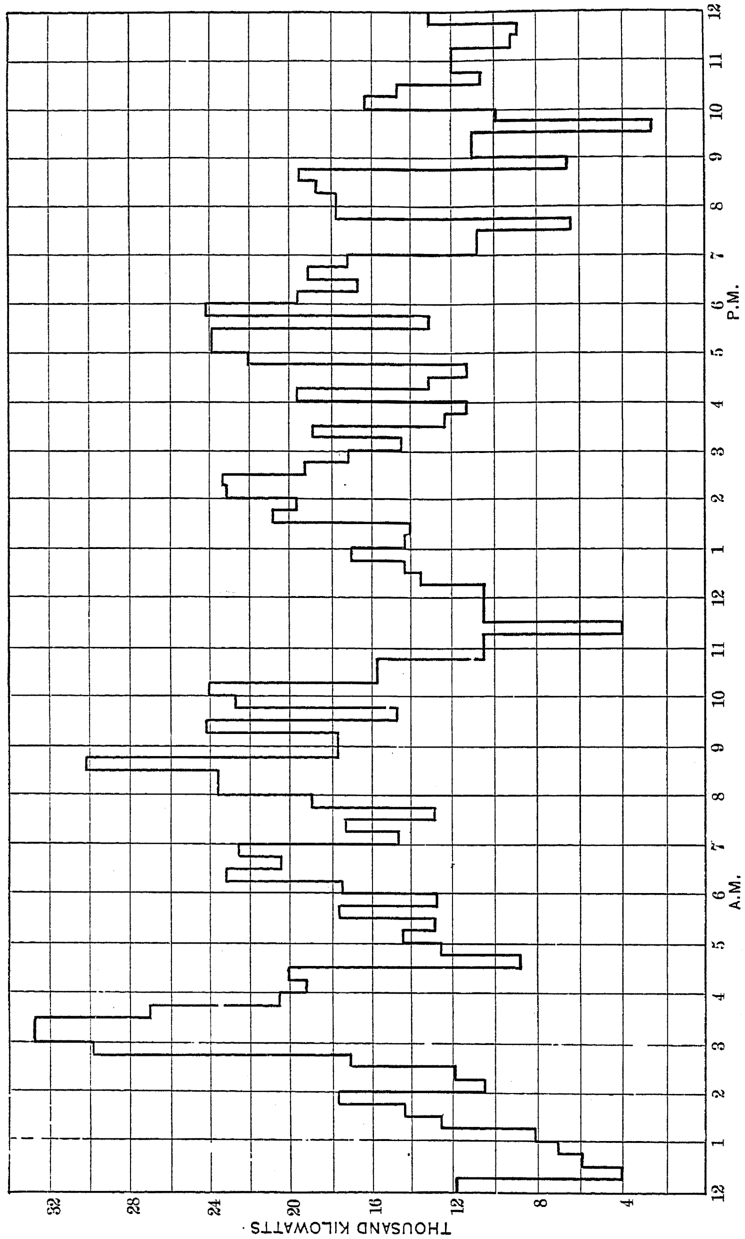


FIG. 6—LOAD DIAGRAM

between 13,000 and 14,000 kw. at the same water rate, with a by-pass for the higher overloads.

The segregated estimated prices are as follows:

Three turbines, 18,000 kw. maximum, for two hours	$400,000
Exciters and battery	25,000
Three condensers and drives	65,000
15,000 h.p. boilers, superheaters, stacks, breeching, brick-work, etc	330,000
Pipe, valves, fittings, covering	75,000
Oil fuel sets, fire, oil unloading, house and boiler feed pumps, heaters	30,000
40,000 bbl. oil storage, blow-off, hot well, house tank, etc.	16,000
Crane	12,500
Switchboard and wiring	150,000
Step-up transformers	100,000
Condenser tunnel system	75,000
Superintendence, engineering, drawings, general labor, traveling expense, telegraph and telephone, testing plant, tools, insurance	75,000
Buildings, foundations and excavation	350,000
Incidentals	56,500
	$1,760,000

The very high temperatures in the summer months at the power house location, (which means hot circulating water), require very large condensers.

The station operating force as taken from the average practise in this part of the country is as follows:—

POWER STATION OPERATING COSTS

Labor:

Superintendent of power		$4,000
Steam:		
1 Chief engineer at	$225 per mo.	2,700
3 Watch engineers at	125 " "	4,500
3 Turbine operators at	95 " "	3,420
6 Water tenders at	95 " "	6,840
6 Firemen at	95 " "	6,840
6 Oilers at	85 " "	6,120
3 Wipers at	75 " "	2,700
1 Boiler repairer	120 " "	1,440
1 Boiler cleaner at	85 " "	1,020
1 Machinist at	110 " "	1,320
1 Machinist helper at	90 " "	1,080
1 Clerk at	90 " "	1,080

Electric:

3 Load dispatchers at	125	"	"	4,500
1 Chief operator at	150	"	"	1,800
3 Switchboard operators at	110	"	"	3,960
3 Asst. " "	90	"	"	3,240
3 Dynamo tenders at	80	"	"	2,880
3 Dynamo cleaners at	75	"	"	2,700
2 Meter testers at	110	"	"	2,640

Total power station, labor	$64,780
Repairs, supplies, etc	20,000
Total per year	$84,780

APPENDIX C

Transmission Line

For the distribution of power along the right-of-way to the different substations there will be required 50.5 miles of No. O twin circuit line, with an addition of 20 miles of the same line from the right-of-way to the generating station, making a total of 70.5 miles of transmission line required. The detail costs following are taken from the actual book costs of a similar transmission line installed recently under practically identical conditions.

Twin Circuit Transmission Line Costs—60,000 Volts
(Assume 3 special and 7 standard towers per mile with suspension insulators, 1 ground wire.)

Material:

3 special towers 3650 lb. each at $5\frac{1}{2}$c delv'd..	$600.00	
7 standard " 3200 " " " $4\frac{1}{2}$ "	938.00	
	$1538.00	
Store charges, one per cent	15.38	$1553.38
126 disk type insulators at $2.20	$277.20	
108 strain " " " 1.95	210.60	
42 sets hdw. for suspension insulators at $1.20	50.40	
36 sets hdw. for suspension insulators at 1.40	50.40	
1 mi. 7/16 in. high strength ground wire, 1900 lb. at $3.25 cwt	61.75	
6 mi. No. 0 copper, 10,122 lb. at $22\frac{1}{2}$c	2277.45	
	$2927.80	
Store charges 6 per cent	175.67	$3103.47
		$4656.85
5 per cent for extras, etc		232.85
		$4889.70

Labor:

Blasting and foundations for towers—average	$60.00		
Distribution of steel	2.50		
Assembling	20.00		
Attaching insulators	3.00		
Erecting towers	10.00		
Ten towers per mile	$95.50	$955	
Distributing six cond. and one ground wire		9	
Stringing six cond. and one ground wire		125	
		$1089	
10 per cent for extras and changes		109	$1198.00
			$6087.70

OVERHEAD CONSTRUCTION

Bakersfield and Mojave Terminals and Kern Yards.

Material:

420 40-ft. tubular steel poles at $65		$27,300.00
50 34-ft. tubular steel poles at $40		2,000.00
380 35-ft. wood poles at $7		2,660.00
85 single brackets for wood poles at $4	$340.00	
40 double brackets for wood poles at $7	280.00	
2260 porcelain strain insulators at 26c	587.50	
1235 wood strain insulators at 60c	741.00	
73,500 ft. 7/16 in. high strength steel strand at $2.60 per C	1,911.00	
5500 ft. 5/16-in. iron strand at $1.25 per C.	68.75	
205,400 ft. 4/0 trolley wire at $130.00 per M.	26,710.00	
1800 trolley clamps at 75c	1,350.00	
100 center trolley supports at 80c	80.00	
1800 suspension insulators at 70c	1,260.00	
	$33,328.25	
Store charges 5 per cent	1,666.50	34,994.75
		$66,954.75
Extra material 5 per cent approx		3,225.25
		$70,180.00
8 anchor bridges (erected)		24,000.00
19,100 ft., 1,500,000-cir. mil copper feeder (erected)		21,729.50
		$115,909.50

Labor:

Erection 420 40-ft. steel poles at $35....	$14,700.00	
" 50 34-ft. steel poles at $25.....	1,250.00	
" 380 35-ft. wood poles at $8.50.	3,230.00	
" 425 cross spans at $7.50, $15, and $20..................	7,600.00	
" trolley.....	8,240.00	
	$35,020.00	
2 per cent use of tools...............	700.30	
	$35,720.30	
10 per cent contingencies............	3,573.20	39,293.50
Total......................................		$155,203.00
Called......................................		$155,250.00

The foregoing costs are taken, (except as to insulators), from the book costs of a recent installation.

The method of construction is to span as many tracks as are necessary, without throwing track, to use steel poles at the ends of the span wires and to carry the trolley wires from a secondary span wire without the use of catenary construction.

Annual Costs

The total annual costs for maintenance of transmission and contact systems, based on the costs of similar work in other places, are as follows:—

Overhead and Contact Rail

Supt. of power distribution at $175 per mo.	
Clerk at $75 per month.................................	$3,000.00
50.5 miles high-tension transmission at $50...........	2,525.00
32.5 miles overhead construction at $250.............	8,125.00
65.84 miles main line contact-rail at $150............	9,876.00
21.60 miles sidings contact-rail at $100................	2,160.00
67.34 miles main line bonding at 10 per cent..........	7,548.00
48.99 miles sidings bonding at 5 per cent.............	2,342.00
	$35,576.00
20 miles additional transmission at $50.............	1,000.00
	$36,576.00

In the foregoing, the estimate for bonding is based on the life of the rail in the track under consideration, it being considered that when the rail is replaced the bonds will come out and will have only a scrap value, being replaced then by new bonds.

APPENDIX D

Block Signals

At the present time the entire district between Mojave and Bakersfield is protected with automatic block signals of the usual continuous-current track circuit battery type. In case of electrification a great part of this apparatus will have to be replaced with alternating-current track circuit apparatus, because the use of track circuits with propulsion current in the rails requires selective apparatus to prevent false indications. The estimate of the signal department for making these changes is $175,000.

APPENDIX E

Electric Shops and Inspection Shed

For the reason that the company has important division shops located already at Bakersfield, a large item for repair shops is not necessary, it being understood that the heavy electric locomotive repairs would be done in the steam locomotive repair shops. An inspection shed with pits, however, is necessary, for which the lump item of $10,000 was included, this being in the ratio of cost of the track facilities required here to the cost of similar track facilities in a shop recently erected by this company.

Note. The maintenance cost of inspection shed and tools therein is carried under the heading of "Locomotive Repairs"—(see Appendix I).

APPENDIX F

Electric Locomotives

An analysis of the train sheets covering the period of maximum tonnage over the mountain shows that there will be required 47 freight locomotives, and 11 passenger locomotives, which includes a reasonably large allowance, namely, 8 freight and 3 passenger locomotives, for repair and shopping purposes. The locomotives required for this service are so closely similar in characteristics to those upon which quotations were asked recently from the electrical manufacturers that new quotations were not requested for the purposes of this estimate, particularly since the locomotives actually quoted on were for the same operating voltages, etc., as are contemplated herein.

The unit costs were: passenger locomotives $40,000, and freight locomotives $35,000, making a total of $2,085,000 for 47 freight and 11 passenger locomotives.

APPENDIX G

Steam Locomotive Credits

It seems pertinent here to note the very significant fact that while steam locomotives are strictly interchangeable and can be moved from division to division as the necessity for varying motive power capacity develops, by reason of crop movements, or otherwise, the electric locomotives are limited in their field of operation strictly to electrified track, and as far as interchange between divisions is concerned they might as well be of some gage other than standard. An inspection of the records of the operating department shows that during a period of heavy traffic over the mountain there were in actual service 13 passenger, 47 consolidated or decapod and 13 Mallet locomotives, which, if taken at the same valuation as was used in a recent report on the Sierra-Nevada electrification, would represent an investment of $1,220,750, to which should be added at least 20 per cent for extras, shopping, repairs, etc., making the total investment in steam locomotives properly chargeable to this district = $1,464,900. It may be thought that the allowance of 20 per cent for shopping, etc., is not large enough; that the records of the steam motive power department will show a greater percentage of locomotives assigned to a given district and actually out of service; but it should be remembered that in case of sudden demands, steam locomotives are moved from division to division as stated above, and therefore it is not reasonable to charge to this district the total amount of steam motive power that would be required if the district is considered as an isolated entity in operation, as would be the case under electric operation.

APPENDIX H

Maintenance of Way as Affected by Locomotives

Many years' experience in the analysis of track maintenance accounts has shown that, independent of all other considerations, track maintenance as affected by rolling stock can be divided into two heads, locomotives and cars, the segregated costs of which have been determined very accurately. Reduced to dollars and cents, the auditor's accounts show that locomotives of approximately the same weight and run at the same speeds as those contemplated in this report, caused maintenance of way expense at a certain rate per locomotive mile, from which has been deduced the item, $83,285, given in the statement of Annual Operating

Costs. That for steam operation, $126,890, is taken from the records.

APPENDIX I

Locomotive Repairs

The figure given under this item for steam operation is taken directly from the records. The estimated cost of electric locomotive repairs, 4 cents per locomotive mile, is based on our analysis of the best data available for such costs. As to this value, opinions reasonably may differ, but it probably will be recognized that the figure named gives a rather favorable consideration to the use of electric locomotives, since the repair accounts of some of the larger railroads operating the largest electric locomotives in this country show repair costs materially more than 4 cents, all things considered.

APPENDIX J

Enginemen's Wages

In the report it was mentioned that certain items, such as freight enginemen's wages, would not be changed materially by a change in the nature of the motive power. The reason is that the present tendency is toward the operation of large Mallet locomotives, at an advanced rate per 100 miles paid their enginemen. Since the capacity of an electric locomotive unit is essentially the same as the largest Mallet it is felt that the wages paid will have to be the same as for present freight service. The passenger enginemen's wages under electric operation are based on the same wages per locomotive mile as under steam operation, but since the electrics would make unnecessary the use of helpers on the mountain, the total has been reduced by the amount now paid helper enginemen.

APPENDIX K

Fuel

The item $240,852 for fuel under steam operation is taken from the records. It represents the oil issued to the steam locomotives and charged to them at the division cost of oil, which in turn is the cost at the wells, plus transportation charges to the particular division, with a percentage added for store expense and handling.

On the other hand, the item $100,530 for fuel under electric operation, represents the number of barrels of oil estimated to

be consumed in the generating station, at the cost per barrel of oil at the wells plus a small handling charge.

The reasons for locating the generating station at the wells are given in detail in Appendix B. The net result is that the oil costs materially less in the steam generating station than when delivered to the locomotives of the San Joaquin division.

The basis upon which the oil consumption is calculated is as follows:

PHYSICAL CHARACTERISTICS OF TRACK

	West slope	East slope
Distance (feet)	261,300	96,624
Total ascent—east	3,687	5
" " —west	77	1,280
" " —east and west	3,764	1,285
Total curvature	7,944 deg.	765 deg.
Ave. grade per cent	1.44	1.33
" curvature	3 deg.	0.79 deg.

TRAIN RESISTANCE, POUNDS PER TON

	West slope	East slope
Grade	28.8	26.6
Curvature	2.7	0.7
Friction	6.0	6.0
Total	37.5	33.3

Energy, foot-tons per ton of train lifted to Summit:

$$\text{West slope } \frac{37.5 \times 261{,}300}{2000} = 4900 \text{ ft-tons}$$

$$\text{East slope } \frac{33.3 \times 96{,}624}{2000} = 1607 \text{ ft-tons}$$

TONNAGE CONSIDERED

Passenger:

One	250-ton train each way plus 150-ton locomotive		400 tons
One	350 " " " " " 150 " "		500 "
Three	400 " " " " " 150 " "		1650 "
Two	600 " " " " " 150 " "		1500 "
Total per day each way			4050 "

Freight:

	Eastbound	Westbound
Gross tons per year (trailing)..........	4,798,056	3,167,301
Number of 500 -ton units..............	9,598	6,335
Number of locomotives(minimum)......	9,598	6,335
Add 10 per cent for underloaded locomotives..........................	960	633
Total locomotives.................	10,558	6,968

Summary:

Gross tons per year trailing............	4,798,056	3,167,301
Locomotives at 100 tons...............	1,055,800	696,800
Total tons per year..................	5,853,856	3,864,101
" " " day....................	16,040	10,600

FUEL CONSUMPTION

Passenger: 4050 tons east and west per day.

East 4050 × 4900.......	19,845,000 ft-tons	
West 4050 × 1607......	6,508,350 "	
	26,353,350 "	
Add 10 per cent for slow movements and starts.....	2,635,335 "	
		28,988,685 ft-tons

Freight:

16,040 tons east per day
10,600 " west " "

East 16,040 × 4900.....	78,596,000 ft-tons	
West 10,600 × 1607.....	17,034,200 "	
Total................	95,630,200 "	
Add 10 per cent for slow movements and starts...	9,563,020 "	
		105,193,220 ft-tons
Total passenger and freight energy per day...		134,181,905 ft-tons

$$\text{H.p-hr. per day } \frac{134,181,905 \times 2000}{33,000 \times 60} = 135,537$$

Based on previous detailed studies of similar problems we are safe in assuming 70 per cent efficiency from power station to locomotive wheels = 144,600 kw-hr. per day at the power station
= 52,779,000 " " year " " "

Requiring, at 210 kw-hr. per bbl. of oil, 251,330 bbl.

Costing, at \$0.40 per bbl., \$100,530.

NOTE. The 70 per cent average efficiency given above is deduced from the following average all-day efficiencies of the plant as designed:

Transmission line	98 per cent
Conversion apparatus	90 per cent
Contact system	87½ per cent
(This being the ratio of the average volts 2100, to the generated volts 2400).	
Locomotives	90 per cent

making a net efficiency of 69½ per cent, which for practical purposes has been called 70 per cent.

Since the position of all trains on the track is known with great accuracy from the train dispatcher's sheets, it is expected that substations on which there is no load will be shut down completely until the train dispatcher advises the station operator that a load is approaching his substation. The foregoing accounts for what may be considered a high average conversion efficiency.

NOTE. In order to show how closely to the average the tonnage runs from month to month, the table of tonnages for the fiscal year 1911-12, is given in Appendix L2.

Fig. 7 gives the train diagram for the conditions of traffic under which this estimate is made. It shows only those trains that are running up-hill, no account being taken of the down-hill trains for obvious reasons. Of course this is not strictly accurate because the trains will consume some small energy in supplying air for brakes, etc., and in occasional movements into and out of sidings, but the error in estimating the probable down-hill use easily may be greater than the total energy consumption of the down-hill trains.

From the foregoing train diagram is made the load diagram given in Fig. 6, the method being as follows:—As has been stated

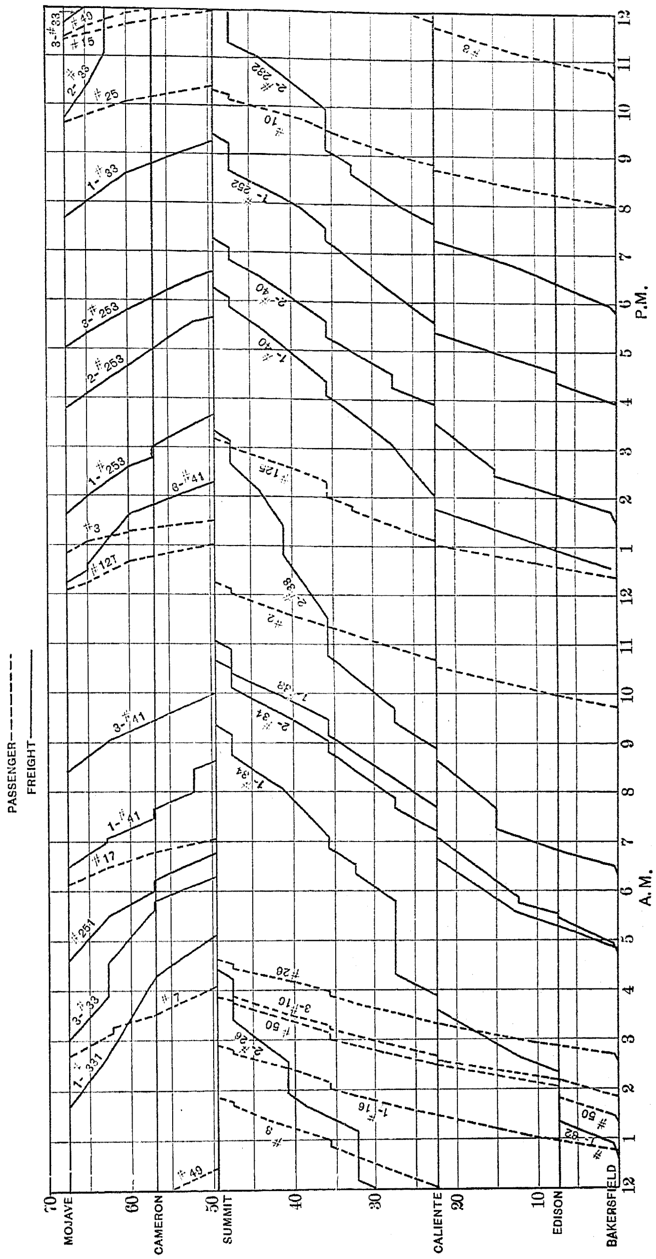


FIG. 7—TRAIN DIAGRAM

previously, in determining the load diagrams from the train diagrams, certain close approximations were made as regards ruling grades, curves, and average grades. Obviously, if a load diagram were made from the actual track plans and engineer's profiles, the time and labor consumed would be very great and out of all proportion to the accuracy of the results; in other words, it is believed that with close approximation to actual conditions the results are within the probable error of the more extended operation.

The individual loads for each particular train on the various approximated grades were taken from characteristic curves of locomotives assumed to be used. These individual loads were then plotted against time, and combined train by train to give the load diagram as shown. The average speed of trains was assumed at approximately 30 miles per hour for passenger trains and 15 miles per hour for freight trains. The ordinates representing power used are plotted at 15-minute intervals. The integrated area of the load diagram as shown will not check with the average energy consumption as given in Appendix K, for the reason that the load diagram is intended to represent maximum travel conditions, it being a step in the determination of the generating station capacity and load factor. In this connection it is interesting to note that the load factor of this diagram is practically 50 per cent when determined on the ½-hour basis. Other students of this problem and writers on this subject seem to have deduced their opinions as to load factors from a selected curve, somewhat similar to this. It should be reasonably evident to anyone who thinks on this subject that the load factor one is concerned with here is the yearly load factor and not the daily. Taken on the basis of the maximum hour and the average year, the load factor of this installation would be close to 20 per cent.

For the information of those who are not familiar with the actual track conditions on the Tehachapi Mountain, the condensed profile is given in Fig. 1; also the tunnel characteristics are given in Appendix L1.

APPENDIX L1

Tunnel Clearances, etc.

Tunnel No.	Length	Height	Curvature	Lining material
1/2	539.5	17ft.to18½ft.	10 deg.	Timber
1	245.8		10 "	"
2	232.2		10 "	"
3	707.7		0	"
4	256.3		10 deg. 05 min.	"
5	1145.9		0	"
6	303.7		10 " 10 "	"
7	532.7		10 "	Rock
8	690		0	Timber
9	426.2		0 " 20 "	"
10	306.6		10 "	"
11	158.8			Rock
12	756.3		10 "	Timber
13	513.8		10 "	"
14	512.7		10 " 04 "	"
15	360.7			"
16	262.5		10 "	"
17	260.9		10 "	"
	8212 ft. =	1.56 mi.		

60 per cent (approx.) of total length is on 10-deg. curve.

APPENDIX L2

Tonnage, July 1, 1911 to June 30, 1912.

July, 1911	564,201
August, 1911	638,665
September, 1911	640,178
October, 1911	666,807
November, 1911	671,708
December, 1911	683,618
January, 1912	688,883
February, 1912	701,846
March, 1912	694,475
April, 1912	666,762
May, 1912	712,251
June, 1912	635,963
Total	7,965,357
Average month	663,780

	Tons	Per cent of average
Minimum month	564,201	85.05
Maximum "	712,251	107.2

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 10, 1913.

THE GULF OF GEORGIA SUBMARINE TELEPHONE CABLE

BY E. P. LA BELLE AND L. P. CRIM

The recent laying of a continuously loaded submarine telephone cable, across the Gulf of Georgia, between Point Grey, near Vancouver, and Nanaimo, on Vancouver Island, in British Columbia, is of interest as it is the only cable of its type in use outside of Europe.

The purpose of this cable was to provide such telephonic facilities to Vancouver Island that the speaking range could be extended from any point on the Island to Vancouver, and other principal towns on the mainland in the territory served by the British Columbia Telephone Company.

The only means of telephonic communication between Vancouver and Victoria, prior to the laying of this cable, was through a submarine cable between Bellingham and Victoria, laid in 1904. This cable was non-loaded, of the four-core type, with gutta-percha insulation, and to the writer's best knowledge, is the only cable of this type in use in North America. This cable is in five pieces crossing the various channels between Bellingham and Victoria. A total of 14.2 nautical miles (16.37 miles, 26.3 km.) of this cable is in use. The conductors are stranded and weigh 180 lb. per nautical mile (44.3 kg. per km.). By means of a circuit which could be provided through this cable by way of Bellingham, a fairly satisfactory service was maintained between Vancouver and Victoria, the circuit equating to about 26 miles (41.8 km.) of standard cable. All communications to points on Vancouver Island north of Victoria were routed through this cable circuit. As a consequence the speaking range from Vancouver to the Island was limited to a few points near Victoria,

and Nanaimo was the extreme limit of commercial service, and conversation was not attempted except under the most favorable conditions. Under some conditions conversation was possible except for the distorting effect of the unloaded cable.

By using the new cable, Nanaimo is made the center of distribution for Vancouver Island. The longest line that will ever be connected at Nanaimo will extend to the north end of Vancouver Island, and will be about 250 miles (400 km.) in length, so it can readily be seen that satisfactory service may be established to any point on Vancouver Island through the new

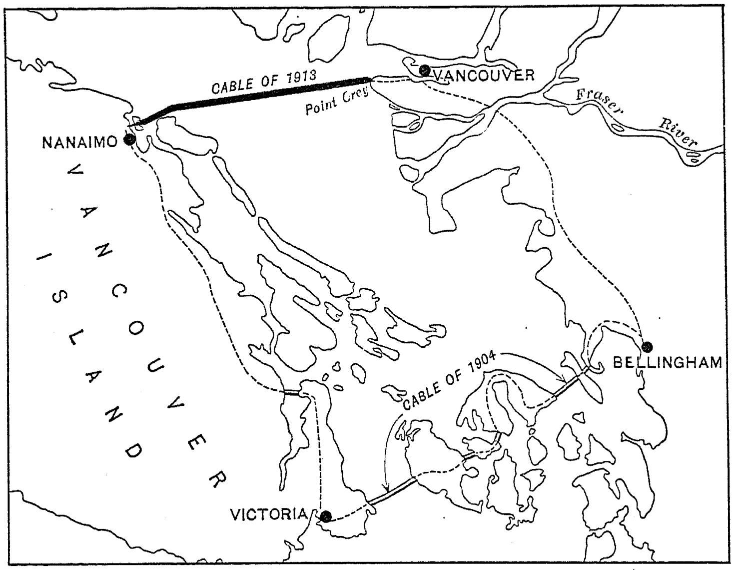


FIG. 1—ROUTE OF CABLES OF 1904 AND 1913. BROKEN LINES INDICATE AERIAL LAND LINES.

cable. It was with the idea in mind of using Nanaimo as the distributing center that the existing route was chosen for laying the cable.

It is quite important to the long life of a submarine cable that a rock bottom and exposure to tidal currents be avoided as much as possible. It is also quite essential that the shore ends be landed in mud or sand and that they be kept buried, at least as far as the low water line. It is believed that the route chosen will prove to be very satisfactory.

The new cable was manufactured by the Henley Telegraph Works, in England, and has the following mechanical properties:

Conductors. Four conductors, each consisting of a central wire, surrounded by twelve wires of annealed copper, having a total weight of 300 lb. per nautical mile (73.4 kg. per km.); total diameter of conductor 0.1385 in. (3.518 mm.).

Loading. One soft iron wire 0.012 in. (0.305 mm.) in diameter, wound round the conductor and having seventy turns per inch (27.6 turns per cm.).

Dielectric. Three coats of best gutta-percha alternating with three coats of Chatterton's compound. Total weight of dielectric per nautical mile 300 lb. (73.4 kg. per km.). Diameter over gutta-percha 0.409 in. (1.04 cm.).

Cabling. Four cores laid around a yarn center, wormed, brass taped and served with yarn.

Armoring. Fifteen galvanized steel wires each 0.192 in. (0.487 cm.) in diameter, separately tarred and served with tarred yarn.

Outer Serving. Two coats of tarred yarn, and two coats of preservative compound.

Diameter. Diameter of completed cable 1.956 in. (4.97 cm.).

Weight. Weight of completed cable, eight English tons per nautical mile (4.38 metric tons per km.).

The same type of armoring was used throughout, and on account of the armor wires each being served with tarred jute, the completed cable was very flexible.

The cable has the following electrical qualities, as measured on 31.3 nautical miles (58 km.) of the completed cable in the factory at a temperature of 75 deg. fahr. (24 deg. cent.). All quantities per nautical mile.

	Conductor resistance	Electrostatic capacity	Dielectric resistance*
	Ohms	Microfarad	Megohms
No. 1 Core	4.004	0.3449	258
No. 2 Core	4.004	0.3455	256
No. 3 Core	4.004	0.3449	268
No 4 Core	4.005	0.3449	274

*After one minute's electrification.

PER NAUTICAL MILE OF LOOPED CIRCUIT

	Cores	Conductor resistance	Electrostatic capacity
		Ohms	Microfarad
Circuit A	1 and 3	8.008	0.1724
Circuit B	2 and 4	8.009	0.1726
Superimposed or phantom circuit on A and B		4.0045	0.3450

The following values were obtained by an eminent independent testing authority on a length of one-twentieth of a nautical mile cut from the completed cable. Results are per nautical mile, and tests were made with sinusoidal current at a frequency of 800 cycles per second, at a temperature of 56 deg. fahr. (13 deg. cent.).

Column A, loop or side circuit cores 1 and 3
" B, " " " " " 2 and 4
" C, superimposed or phantom circuit.

	A	B	C	
Effective resistance R	9.16	9.14	4.69	ohms
Effective inductance L	11.56	11.54	5.45	millihenrys
Effective capacity K	0.1647	0.1662	0.3338	microfarad
Effective leakance S	12.24	11.26	19.84	microhms
Ratio S/K	74.3	67.8	59.4	
Attenuation constant	0.01892	0.01874	0.01966	

The following results were obtained in the laboratory of the manufacturers on the completed length of 31 nautical miles (58.5 km.) coiled up in the iron tank and covered with water, using sinusoidal current at 800 cycles per second, as before.

Circuit	A	B	
Open impedance Z_O	349.35	337,4	Vector ohms
	\32°31′	\33°54′	angle
Closed impedance Z_C	185.75	187.5	Vector ohms
	/23°53′	/24°43′	angle
Characteristic impedance Z	254.5	251.4	Vector ohms
	\4°19′	\ 4°56′	angle
Attenuation constant	0.01946	0.01940	

After laying, the cable was tested for dielectric resistance, for capacity, and for conductor resistance. The transmission equivalent was measured in terms of standard cable and tests were made for crosstalk.

SUMMARY OF TESTS AFTER LAYING

	Conductor resistance	Mutual capacity
	Ohms	Microfarad
No. 1 Circuit	8.008	0.175
No. 2 Circuit	8.008	0.174

	Electrostatic capacity	Dielectr'c resistance
	Microfarad	Megohms
No. 1 Core	0.347	445
No. 2 Core	0.349	451
No. 3 Core	0.351	461
No. 4 Core	0.347	461

The above results are per nautical mile. Dielectric resistance is corrected to 75 deg. fahr. (24 deg. cent.).

The actual length of cable in use is 28.3 nautical miles (52.5 km.) and its mean temperature was 49.6 deg. fahr. (9.8 deg. cent.) at the time the measurements were taken. Speech tests showed a standard cable equivalent of eight miles with zero loop on each end, and 5.75 miles, with 12 miles of standard cable at each end to reduce reflection losses.

The finished cable was shipped from England to Vancouver on the ship *Crown of Galicia*. It was stored in a steel tank while on shipboard and kept under water. The temperature was observed daily throughout the voyage. Upon arrival at Vancouver, it was transferred from the tank in the hold of the *Crown of Galicia* to the hold of the barge *Princess Louise*, from which it was later laid. The actual operation of laying was begun at the Point Grey end at 4 a.m. June 16th, and finished at Kanaka Bay on New Castle Island at 7:30 the evening of the same day. The illustrations herewith show the laying operations in detail. Throughout the entire operation of laying, one pair was under continuous test for insulation resistance, while the other pair was being utilized for communication with the shore. As a matter of precaution the two pairs were interchanged at intervals so that no fault in the dielectric could escape observation for any length of time. While the cable was being laid, conversations were carried on with parties in Vancouver, Victoria, Seattle and Portland. Two tugs were used to tow the cable ship, which was without power of its own. Telephonic communication was maintained with the tugs by means of rubber covered wires strung on the hawser. Observations to determine the location were taken at regular intervals with a sextant, and a log of operations was carefully kept. The tension on the cable was observed by means of a dynamometer, and the amount of cable paid out was read from the rolometer attached to the paying-out drums. With the exception of a light rain in the morning, the weather was excellent, and a number of guests observed the laying operations, which were without accident.

A cable hut is provided at each of the shore ends for housing the protective apparatus and making the connections between the cable and the aerial land lines. The protective apparatus is of the Lodge-Muirhead type, and consists of three reactive coils with four discharge points, located around a central brass disk, which is grounded to the armor wires of the cable. Each of the cable cores is led through a protector of this type, and a fuse is inserted between the protector and the line wire, and also between the protector and the cable. All of the protective apparatus is housed in a waterproof cast iron case.

The two physical circuits provided in this cable were satisfactory in every way and are each equivalent to about 5.75 miles of standard cable. The phantom circuit, however, is not so satisfactory. It is only fair to the manufacturers, however, to state that a satisfactory phantom circuit was not guaranteed. It will be seen that the capacity and leakance of the phantom circuit is just two times as great as in the physical circuits, while the resistance and inductance are about one-half each. This causes the attenuation constant of the phantom to be somewhat greater than that of the physical circuits. There is also some crosstalk between the physical circuits and the phantom, being equivalent to a conversation through about 75 miles (120 km.) of standard cable. Tests for this determination were made with local battery sets, in the cable huts, connected directly to the ends of the cable. This crosstalk is undoubtedly caused by inductive unbalance in the cable. On account of the salt water penetrating to the outside core of the gutta-percha, the wires are shielded from each other electrostatically. Any disturbance that is transmitted from one wire to another must therefore be of an electromagnetic nature. The capacity of the cores in this type of cable depends upon the thickness of the dielectric, and in every case is the capacity from the wire to the ground (salt water), as the sea water penetrates the cable to the gutta-percha. Efforts to decrease the capacity of this type of cable by a paper wrapping under the gutta-percha, in order to increase economically the diameter, have failed because of the moisture content of the gutta-percha being absorbed by the paper.

The uniformity of the capacity then depends upon the cores being exactly of the same dimensions and located symmetrically. It can readily be seen that a slight eccentricity of conductor in the dielectric will change the capacity accordingly.

The inductance of these cable circuits is artificially increased

by a winding of soft iron wire around the copper conductor, which increases the permeability of its magnetic field. This is the well-known Krarup system of continuous loading. The permeability of this wire may be affected in three ways, namely, aging, by straining it beyond its elastic limit, and by permanently magnetizing it. Aging occurs in nearly all iron used in magnetic circuits and the magnitude of the change of permeability varies with the different pieces of iron. It is thus possible that the inductance of the different cores of a Krarup cable might be thrown out of balance by the iron wires aging differently. It is known that the permeability of magnetic iron is affected by straining it beyond its elastic limit. When it is considered that the loading wire is only 0.012 in. (0.305 mm.) in diameter, and that in order to hold it around the copper conductor so that it will remain evenly distributed, it is necessary to apply it with considerable tension, it is more than likely that a considerable amount of this wire has been heavily strained. This is indicated by its appearance. During manufacture the different sections of core were spliced together in such a way as to neutralize as far as possible any unbalances that could be detected at that time. It will be seen that the total capacities and inductances of the different cores are in a fair degree of balance. There is very little danger of the iron wrapping used in continuous loading ever becoming permanently magnetized, as this would require a very heavy current.

It is customary to measure the direct-current insulation resistance of a gutta-percha core at 75 deg. fahr. (24 deg. cent.) and after one minute's electrification. The insulation resistance increases quite rapidly after the initial electrification and only reaches a fairly constant state after some time. This effect, although not well understood, seems to be somewhat similar to the polarization effect of an electrolytic couple. The dielectric resistance so obtained cannot be used to deduce the leakance S for calculating the attenuation constant and circuit impedance. Measurements for this quantity must be made at telephonic frequencies and voltage, and owing to the extremely small quantity of power involved, are exceedingly difficult to make with any degree of precision.

Gutta-percha is rarely employed as an insulator for telephone conductors, with the exception of submarine cables in deep water. While information regarding its various characteristics is not very plentiful, a brief statement of its qualities may be of interest.

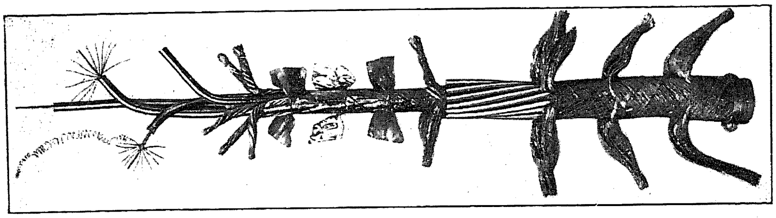
It is composed of pure gutta, rosin and water. It is a vegetable gum secured from certain tropical trees very much the same as India rubber. It is collected by native labor, and shipped in the raw state to the factory where it is prepared for commercial use. The first step in its preparation is to remove all impurities, as far as possible, which is done by boiling in water. It is then put through a masticating machine, after which it is rolled out into thin sheets.

The wire which is to be insulated with gutta-percha is first given a coat of Chatterton's compound, and then a coat of gutta-percha is applied with a sheathing machine, in much the same manner as lead sheaths are applied to the ordinary paper-insulated telephone cable. Additional layers are applied, alternating with layers of Chatterton's compound, until the required thickness of dielectric has been obtained. It should be noted that gutta-percha is not subjected to any process similar to the vulcanization of rubber, but is used in the raw state. It contains no sulphur, and copper wires do not require tinning before being insulated with gutta-percha.

In general, rosin increases the initial insulation resistance of gutta-percha, but if it is present in too great proportions it tends to separate, especially upon exposure to heat and light, and causes cracks to form in the insulation. Ordinary grades contain from five to six per cent moisture. The insulation resistance increases very rapidly with a decrease in temperature, so that at 45 deg. fahr. (7.2 deg. cent.) its insulation resistance is about ten times that at 75 deg. fahr. (24 deg. cent.). If it is heated much above 80 deg. fahr. (27 deg. cent.) it soon softens, and in a completed cable this would allow the cores to become deformed, especially if the cable were subjected to any considerable pressure, such as the lower coils in a cable tank. Instances have been known where the copper conductor by its own weight became so eccentric in the core that a large quantity of the cable was ruined on account of the insulation becoming too thin.

Generally speaking, if different grades of gutta-percha are mixed together, a higher dielectric resistance is obtained, but the fibrous structure is not so good as if one quality were used throughout.

The splicing of a gutta-percha-insulated conductor is one requiring no little skill and care. It is necessary in splicing a four-core cable that the spliced conductors be of equal length, so that no one splice will be subjected to more than normal



[LA BELLE AND CRIM]

FIG. 2.—DETAILS OF CABLE CONSTRUCTION.

[LA BELLE AND CRIM]

FIG. 3.—COILING OF CABLE IN HOLD OF *Princess Louise*.

PLATE LVIII
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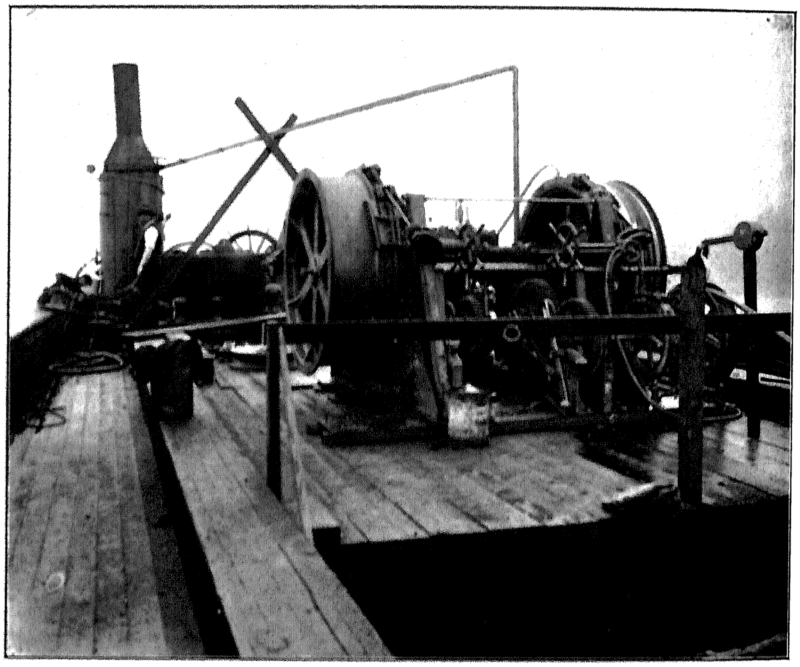
VOL. XXXII, 1913

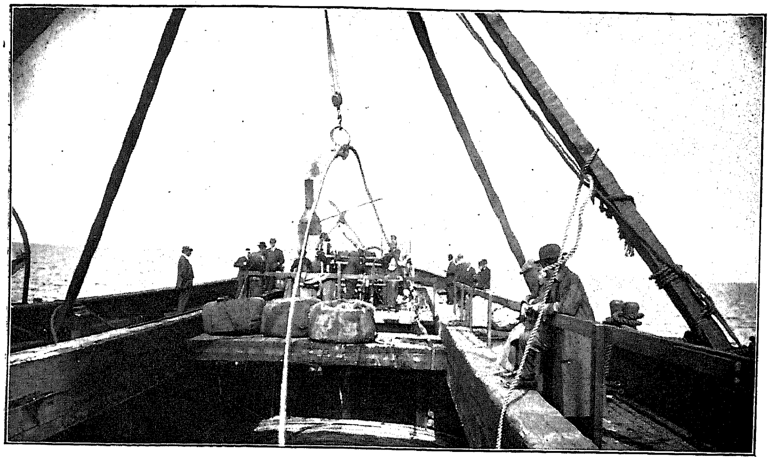
[LA BELLE AND GRIM]

FIG. 4.—CABLE IN TANK ON BOARD *Crown of Galicia*.



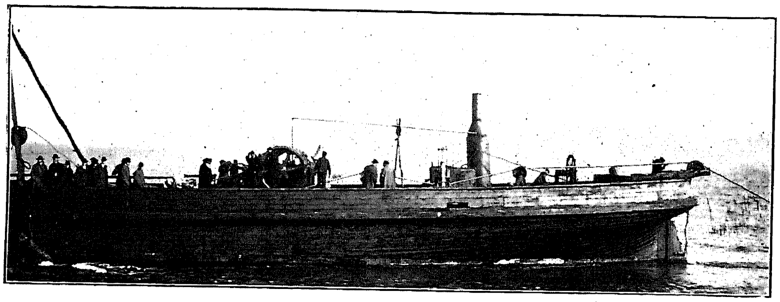
[LA BELLE AND GRIM]

FIG. 5.—PAYING-OUT DRUMS.



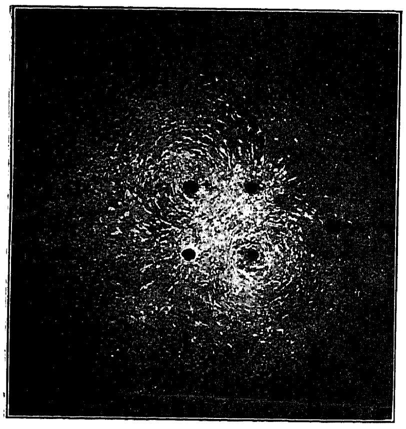
[LA BELLE AND CRIM]

FIG. 6.—CABLE LAYING GEAR IN OPERATION.



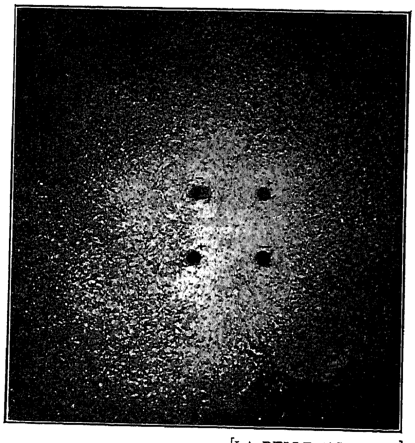
[LA BELLE AND CRIM]

FIG. 7.—SIDE VIEW OF CABLE SHIP UNDER WAY



[LA BELLE AND CRIM]

FIG. 8.—DISTRIBUTION OF MAGNETIC FLUX IN FOUR-CORE CABLE, CURRENT FLOWING IN PHYSICAL CIRCUIT ONLY.



[LA BELLE AND CRIM]

FIG. 9.—DISTRIBUTION OF MAGNETIC FLUX IN FOUR-CORE CABLE, CURRENT FLOWING IN PHANTOM CIRCUIT.

stress. In splicing the conductors, the ends are scarfed and soldered together. Then the joint is given a close wrapping of fine copper wire, which is also soldered all over. A second wrapping of fine copper wire is then applied in reverse direction and soldered only at the ends. In case the joint was so strained as to break the soldering in the main conductor and the first wrapping of copper wire, this last spiral wrapping would still form a metallic connection across the break. In joining the dielectric, the same number of layers of gutta-percha are applied, alternating with Chatterton's compound, as are used in the manufacture of the core. The gutta-percha is warmed with a spirit lamp until plastic, and is applied with the fingers. The finished splice must not have a much greater diameter than the unspliced core and must show leakance not in excess of a piece of core ten times the length of the splice. Owing to the inability of gutta-percha to stand exposure to moderately high temperature, light and air, it has been the practise among European engineers to splice a piece of rubber-insulated cable on to the gutta-percha below the water level at the shore ends, and thus make the landing with rubber-insulated cable. As it is well nigh impossible to make a perfect splice between rubber and gutta-percha, it is necessary to employ a water-tight junction box if this method of terminating the shore ends is used. No method has yet been found for cementing rubber and gutta-percha together so that the joint will hold for any appreciable length of time. The practise of using rubber insulation for the shore ends was not followed in laying the Point Grey-Nanaimo cable, for the above reasons. The shore ends have been buried from the terminal in the cable hut to low water, and on account of this, will not be exposed to temperature very much above that of the sea water. Sufficient slack has been left in the cable so that in case the ends at the terminals lose their insulating qualities, they may be cut off and the cable reterminated. In this way the ends of the cable may be kept in excellent condition by allowing a few feet extra for the cable reterminating.

In a four-core cable such as is generally used for telephone purposes in deep water, the two opposite cores are used to form each circuit. It is not necessary, if the cores are arranged symmetrically about the center, that the wires be twisted in pairs in order that each circuit will be unaffected by the current flowing in the other. The wires of one circuit do not inter-loop the lines of magnetic force from the other, and each of the wires

is under the influence of equal and opposite electrostatic fields. This latter is not true of a cable submerged in salt water, due to the shielding effect of the salt water. As mentioned before, it will therefore be seen that the two circuits are quite independent of each other both electromagnetically and electrostatically. The same thing is true of the superimposed or phantom circuit, but the results obtained in practise are not so good as with the two physical circuits.

In selecting a design of cable suitable for this service, the choice was practically limited to a four-core gutta-percha cable, loaded either by the continuous or Krarup system, or by the use of Pupin coils. Owing to the depth of water (1300 feet = 396 meters) a paper-insulated lead-covered cable was not seriously considered. The stress during the laying would so strain the cable in passing over the drums and sheaves that there would be great danger of impairing the insulation between the wires. Owing to the highly distortional effect of non-loaded gutta-percha cable, it was necessary to eliminate such a cable from consideration. It remained, therefore, to choose between the two types of loading. It is well known that a coil-loaded cable is quite superior to a continuously loaded cable, or in fact any other design of cable, when electrical qualities alone are considered. The continuously loaded cable is mechanically quite simple and upon its completion is equally as strong as a non-loaded cable such as has been used for telegraph service for years, even at the maximum depth of the ocean. In a coil-loaded cable the only acceptable design of coil so far employed is one which surrounds the four cores of the cable, and which is taken inside the regular cable armor. This causes an increase in the diameter of the cable from two to three times its unloaded diameter, and in spite of precautions which may be taken in the manufacture, these loaded points are the weakest spots in the cable, both electrically and mechanically.

The two best-known examples of coil-loaded submarine cable extend from England to France across the English Channel, and from England to Belgium. The former cable is about 20 nautical miles (37.1 km.) in length, and the latter about 40 nautical miles (74.2 km.) in length. Neither of these cables is laid in a very great depth of water, and both are under the supervision of the British Post Office, which has available cable ships especially designed for the laying and repairing of such cables. The older of these cables has only been in use about three years, and

during this time no serious case of trouble has developed, so that the actual difficulties to be encountered in repairing this type of cable can only be forecasted in view of experience in repairing the non-loaded type.

In order to keep the transmission in a coil-loaded cable at its original quality, it is necessary that the spacing of the coils be kept as originally laid out, allowing only a variation of five per cent. It is quite obvious that this is not true of the continuously loaded type, and any increase in the length would cause an increase in the transmission loss, only in proportion to the increased length of the cable employed.

In case of a fault in deep water, the cable is picked up by means of a grapnel and as soon as it is brought to the surface it must be cut in order to relieve the great strain. One end is retained, and a line is made fast to the other end, which is thrown overboard with a buoy attached. The cable is then picked up until the fault is located and repaired. It is then necessary to splice in a piece of new cable and pay out until the buoyed end is picked up, when as much slack as practicable is taken out and the two ends spliced together. It will thus be seen that a considerable additional length of cable will be introduced in case of a fault in very deep water. In case such a repair was made at a depth of 1300 ft. (396 m.), under the most favorable conditions, it is quite probable that 800 to 1000 ft. (244 to 305 m.) of additional cable would be introduced. As 300 ft. (91 m.) is the greatest allowable variation with coils spaced one nautical mile (1.854 km.) apart, it will be seen that the coil spacing would be badly disarranged and serious reflection losses introduced. It must also be remembered that no gutta-percha cable is manufactured in America and the only submarine loading coils so far manufactured have been made in Europe, and in case extensive repairs were necessitated, it might be necessary to secure special equipment and skilled labor from Europe, while with the type adopted, repairs can be made with the equipment and labor commonly used in repairing telegraph cables.

Comparisons between the two types of loading have been made and much discussed by different authorities, and a comparatively recent paper on this subject by Mr. J. G. Hill[1] summarizes arguments in favor of the two types in a very excellent manner. It is a well-known fact that the two types of cable having the same

1. "The Loading of Submarine Telephone Cables," by J. G. Hill—*Electrical Review* (London), Nov. 29, Dec. 6 and 13, 1912.

transmission efficiency may be produced, the coil-loaded cable at much less expense than the continuously loaded cable. Mr. Hill bases his comparison on two factors; one, that inductance can be added by the continuous method of loading only up to a certain limit, say 20 millihenrys, while by coil-loading, any desired amount of inductance may be added to the circuit; and second, that the ratio R/L, obtainable with the coil-loaded cable, is much less than that obtained in continuous loading. The limit of economic loading depends upon the amount of resistance added to the circuit in increasing its inductance.

The attenuation constant of a cable is unfavorably affected by the addition of resistance. All known methods of increasing the inductance of a circuit, also increase the effective ohmic resistance, and Mr. Hill compares the efficiency of the added inductance in terms of the amount of resistance so added. It has been found that the ratio between the added resistance and the added inductance for continuous loading is about 110, while a good design of loading coil has a ratio of R/L of about 60. These ratios are true only for the amount of inductance used in ordinary practise. The increase in effective resistance, as is well known, is due to the eddy currents and hysteresis losses in the iron of the magnetic circuit. Eddy current losses can be reduced by subdividing the iron. Hysteresis losses depend upon the degree of saturation of the magnetic field, which is kept low in all telephone circuits. Pupin coils employ a toroidal magnetic core composed of a large number of turns of very fine iron wire with some type of enamel insulation. It is possible to employ several layers of fine wire on a continuously loaded cable, and several have been laid which use three layers. The improvement in the magnetic circuit by such subdividing is not so marked as in the coils, and the expense is very much greater. It would seem that future design will show a still greater advantage in the coil-loaded type of cable, as it is probable that the R/L for loading coils can be reduced still more, economically. It might be of theoretical interest to remark that as the effective resistance of a coil-loaded conductor is a function of the frequency, it is therefore impossible to build a distortionless circuit employing iron magnetic fields.

We can therefore summarize the arguments that we considered in selecting the type of cable as follows:

Arguments in Favor of a Coil-Loaded Cable. 1. Could employ smaller conductors, and less gutta-percha, and secure a cheaper

cable for the same transmission equivalent (disregarding terminal losses).

2. Could give the phantom circuit the same degree of loading as the physical circuits.

3. Could add any desired amount of inductance.

4. Aging of the iron cores of the loading coils could not unbalance the circuits.

Arguments in Favor of a Continuously Loaded Cable. 1. Simplicity of construction.

2. Could be laid and repaired like an ordinary gutta-percha-insulated telegraph cable.

3. Short lengths added in repairs do not materially affect the transmission.

4. Not liable to faults at loading coils.

5. Faults could be located more accurately by means of resistance measurements.

6. Is not heavily loaded, and therefore has less reflection losses at shore ends where it joins to non-loaded open wire lines, than would be the case with a coil-loaded cable.

7. Known to be reliable at the greatest depths of water.

It was after due consideration of the above factors that the continuously loaded type was decided upon, and the results obtained have amply justified the selection.

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 11, 1913.

A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT

BY JOHN B. FISKEN

The substation which forms the subject of this paper was put into service in November, 1910, and is the outcome of seven years' experience gained by the Washington Water Power Company in distributing electric power by means of 60,000-volt lines to the Coeur d'Alene mining district in Northern Idaho.

This substation has been provided for the purpose of supplying three-phase power to the Bunker Hill & Sullivan Mining and Concentrating Company, at 2300 volts. This power is used for all purposes contingent to mining, such as running compressors, pumps, d-c. generators for mine and yard haulage, hoists, saw mills, concentrators, et cetera, and for commercial lighting in the mining towns of Kellogg and Wardner.

As an indication of the evolution of this branch of The Washington Water Power Company's business, it may be stated that when the transmission line from Spokane was put into operation in August, 1903, the substation built at that time for the Bunker Hill & Sullivan mine was equipped with one transformer of 275-kv-a. capacity, whereas the demand now requires three 650-kv-a. capacity transformers. It may be here stated that the introduction of reliable electric power has been the principal factor in making the output of the Coeur d'Alene mining district in lead today the second largest of any district in the world. And not only has this power been of inestimable value to the developed mines of the district, but on account of its low cost and its flexibility and convenience it has enabled prospects to be developed into mines, which without it would have remained dormant for many years.

The location of this substation is fortunate. It is within a distance of 400 ft. (122 m.) from the main transmission lines, which are in duplicate, the branch being provided with air switches to enable it to be connected to either main line. There is a spur from the railroad about 26 ft. (7.9 m.) from the building and at an elevation four ft. (1.2 m.) below the floor level, so that transformers, or other heavy apparatus, can be rolled off the railroad cars and into the building without having to be raised or lowered. The cooling water for the transformers comes from the mine tunnel, the portal of which is at an eleva-

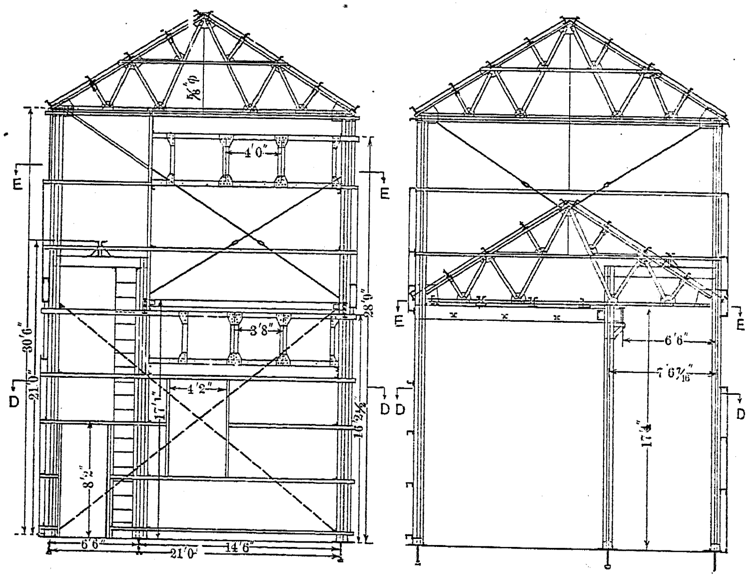
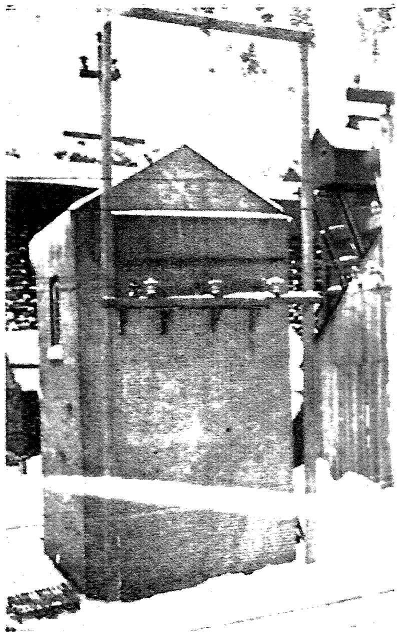


FIG. 1

tion of about 43 ft. (13 m.) above the top of the transformers. The secondary line to the Bunker Hill & Sullivan main switchboard is only about 750 ft. (228.6 m.) in length. These almost ideal conditions are not easily obtained in a rough, mountainous country.

The building consists of a framework of structural steel, covered, both sides and roof, with galvanized corrugated iron, the main columns being supported on concrete footings. The floors are all of concrete, making the building practically fireproof. Figs. 1 and 2 show the details of the steel framework.



[FISKEN]

FIG. 3—FIRST TYPE OF BRICK SUBSTATION

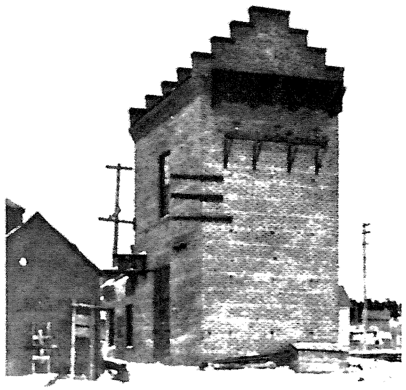


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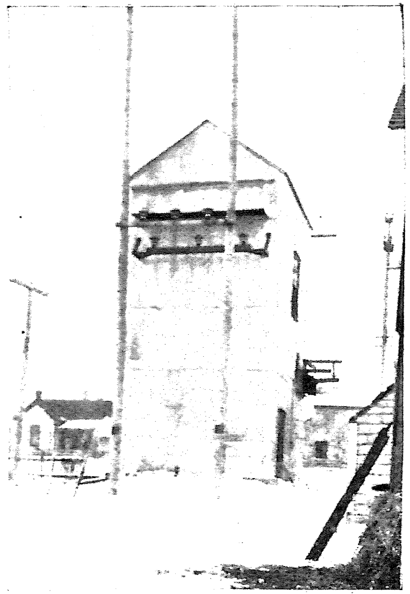
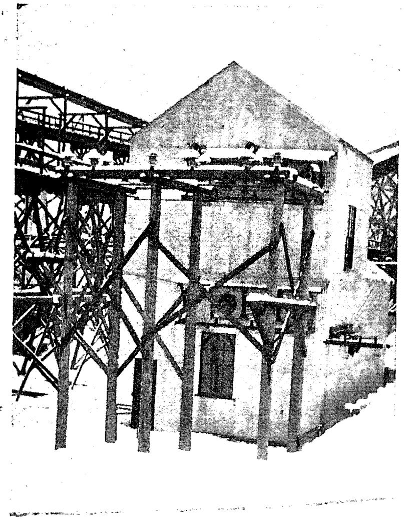
FIG. 4—LATER TYPE OF BRICK SUBSTATION



[FISKEN]

FIG. 5—STANDARD STEEL SUBSTATION

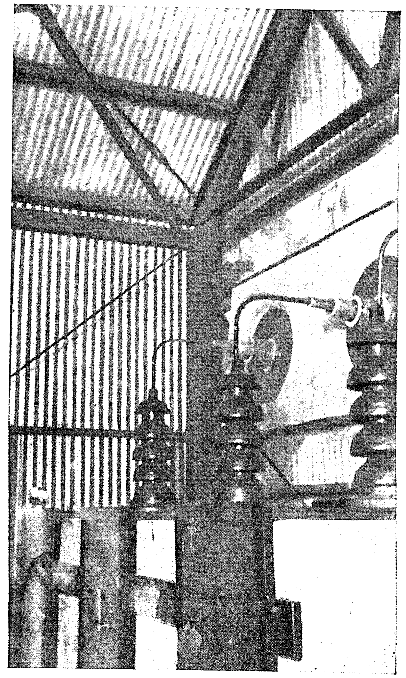


[FISKEN]

FIG. 6—BUNKER HILL AND SULLIVAN SUBSTATION, LOOKING NORTH

[FISKEN]

FIG. 7—BUNKER HILL AND SULLIVAN SUBSTATION, LOOKING EAST



[FISKEN]

FIG. 9—TOP OF LIGHTNING ARRESTER HOUSING

This type of building has been adopted in preference to brick, stone or concrete buildings on account of the ease with which it can, should the occasion arise, be taken down and reerected at some other location. The experience of the Washington Water Power Company has shown that such occasions do arise, in a rapidly growing mining country, due to consolidation

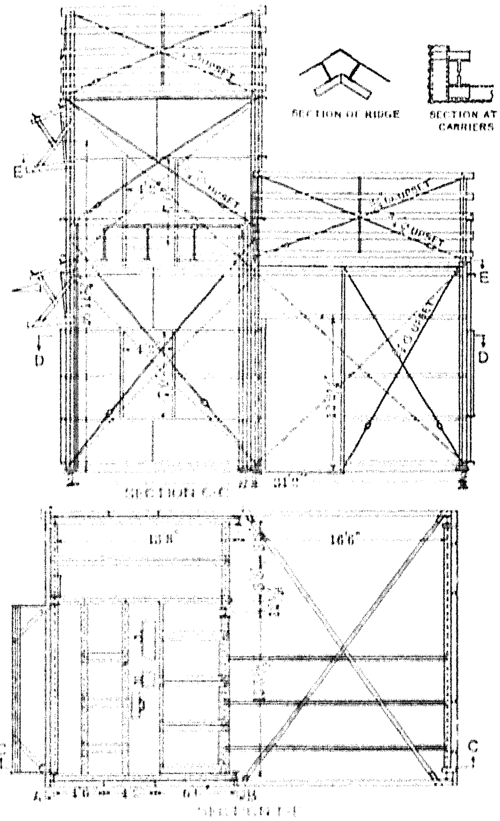


FIG. 2

of adjacent properties and centralization of the works, or to the abandonment of properties which have "played out", or, as in the case of the Bunker Hill & Sullivan mine, to the extensive development of the property.

While the steel type of substation offers no saving in first cost, it has the advantage that if it should have to be moved all that is lost of the first investment is the cost of the concrete

and labor of erection and equipment. This has been demonstrated on several occasions to the satisfaction of The Washington Water Power Company. On the other hand the salvage from a brick building is practically nothing, as the cost of taking it down and cleaning the brick is about all the material is worth. The first type of brick substation is shown in Fig. 3, and a later type in Fig. 4. The first type of steel substation, which is standard for a two-transformer station, is shown in Fig. 5, and Figs. 6 and 7 are exterior views of the Bunker Hill & Sullivan substation.

Outside the substation are located the horn gaps for the lightning arresters, and reactance coils in the supply wires as a further protection to the apparatus.

All incoming wires enter through porcelain wall-tubes set in concrete slabs. These wall-tubes were tested to 135,000 volts when subjected to a precipitation of one inch of water per five minutes without flashing over; to a potential of 155,000 volts for three minutes when dry; and immediately after the last test to a potential of 165,000 volts without flashing over. During these tests the wall-tubes were arranged with their axes in an approximately horizontal position, the connection for potential being made to a metal support in contact with the edge of the disk, and to a metal rod through the center tube.

The lightning arresters, which are of the electrolytic type, are located immediately inside the buildings. As no attempt is made to heat the building, and as temperatures as low as −30 deg. fahr. are not uncommon, it was considered advisable to provide means to keep the temperature of the lightning arresters from reaching a point which might impair their efficiency. This was accomplished by building a housing which can be heated with electric heaters. The housing consists of an open framework of scantlings covered both inside and out with metal lath and plastered with hydraulic cement plaster, the open spaces being filled with loose shavings. To permit of readily removing the arresters, portions of the top of the housing are omitted and openings are left in the front. The openings in the top of the housing are closed after the arresters are in place by means of asbestos slabs, and removable doors built of asbestos slabs strengthened with wooden framework close the openings in front. Fig. 8 shows the details and Fig. 9 gives a general view of the top of the housing with roof insulators and connecting leads of copper tubing.

Fig. 10 shows vertical and horizontal sections of the substation with the apparatus in position.

The main 60,000-volt conductors, which can be opened near their entrance by means of disconnecting switches (see Fig. 11), go through an oil switch to the busbars above the transformers. The oil switch is equipped with a series overload relay in each leg.

The transformers, which are run in multiple, are water-cooled,

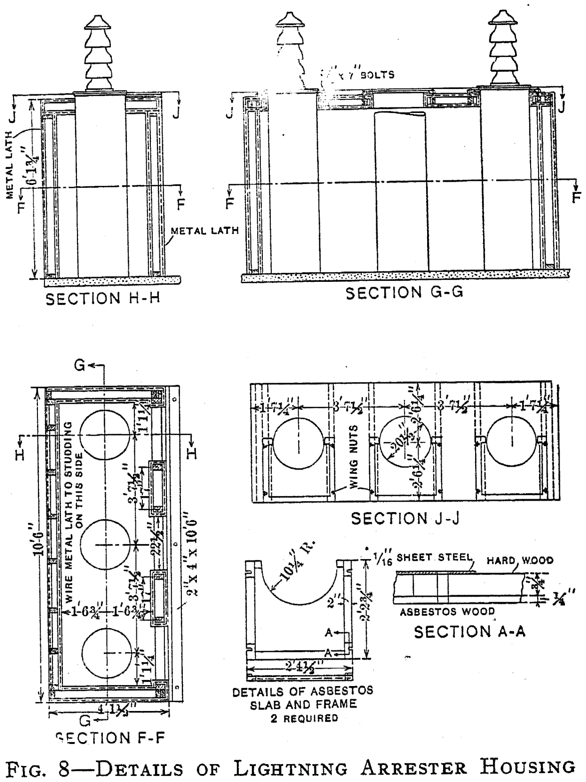


FIG. 8—DETAILS OF LIGHTNING ARRESTER HOUSING

three-phase connected, the primary in Y and the secondary in Δ, the neutral of each high-tension winding being grounded. Three transformers, of 650-kv-a. each, are used instead of one of greater capacity, for the reason that they were available when the station was equipped and spare transformers of that size are kept on hand; it is expected, however, that some time in the future these will be replaced by larger ones, and the building has been designed to admit of the installation of transformers

up to 2200-kv-a. capacity. The use of water-cooled, three-phase, instead of single-phase transformers was decided upon for several reasons when the first transmission line was built into the Coeur d'Alene country. The cost per kilovolt-ampere at the factory was very much less, and a considerable saving was made in freight. The economy in floor space was also a factor, not only on account of the saving in cost of the sub-

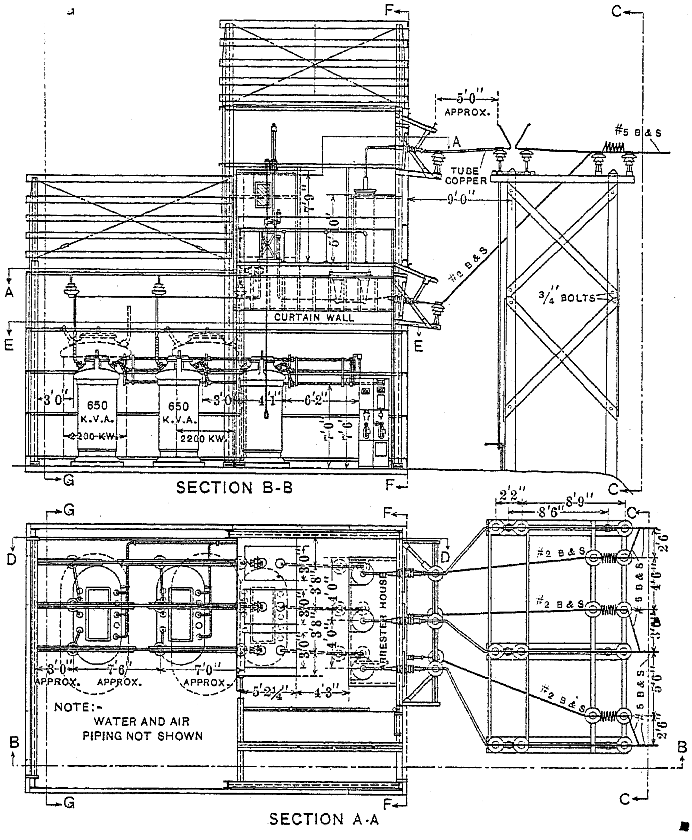


FIG. 10—SECTIONS OF SUBSTATION

station buildings, but owing to the fact that many of the substations had to be located in a canyon where every square foot of available space was valuable, while others had to be located on steep mountain sides. The Washington Water Power Company was among the first, if it was not actually the first company to adopt the three-phase transformer, and the results have been such that after an experience of over ten years,

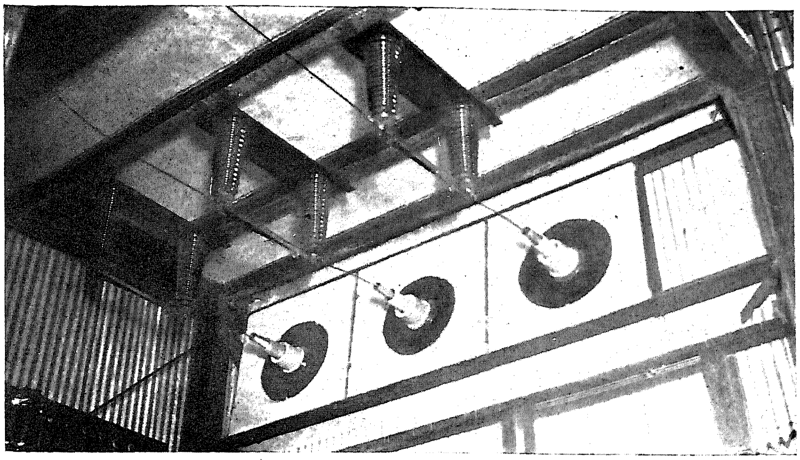


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FIG. 11—DISCONNECTING SWITCHES, 60,000 VOLTS

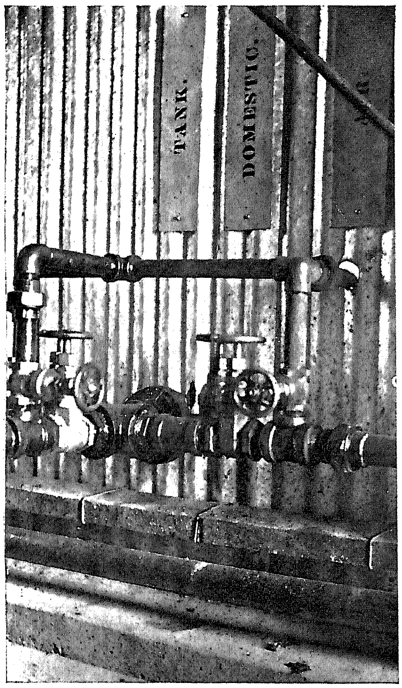

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FIG. 12—INCOMING WATER AND AIR PIPES

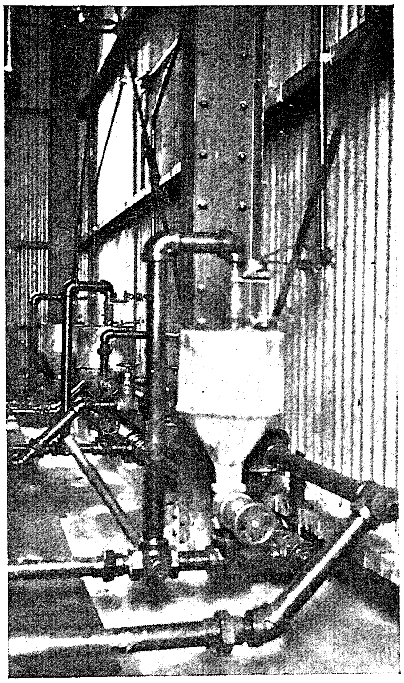

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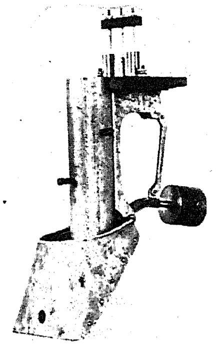
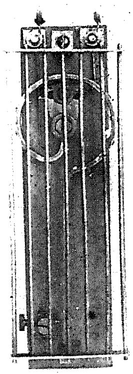
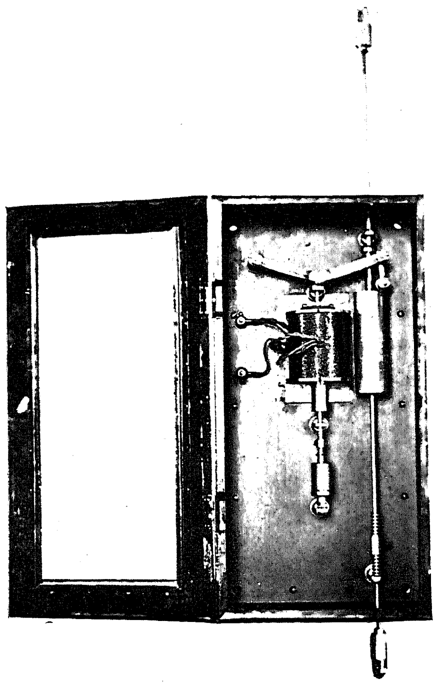
FIG. 13—TRANSFORMER PIPING



[FISKEN]
FIG. 14—WATER RELAY



[FISKEN]
FIG. 15—THERMOSTAT



[FISKEN]
FIG. 17—AUTOMATIC TRIP

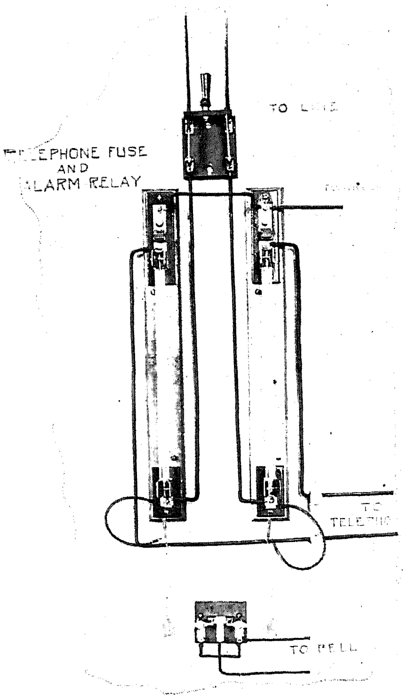


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FIG. 18—TELEPHONE EQUIPMENT

not only in the company's substations but in its generating plants, it continues to purchase them.

The cooling water for the transformers is taken from the mine tunnel through a flume to a storage and settling tank, from which it is piped to the transformers. As the normal flow of water is greater than is required, the level in the tank is constant, and a low water alarm is provided to notify the attendant in the compressor room of the mine if for any reason the supply from the tunnel should be cut off. Provision is made for the use of domestic water, but in the dry, hot summer months, when the water is most required, this is very scarce and it is only used in case of emergency. As this mine water carries considerable solid matter in suspension and as all of it is not deposited in the settling tank, a permanent connection is made to each transformer from the mine air line, and at frequent intervals, what solid matter has settled in the cooling coils is blown out by air at a pressure of about 80 lb. per sq. in. (5.6 kg. per sq. cm.). Fig. 12 shows the incoming water and air pipes and Fig. 13 is a view of the piping back of the transformers.

The water is discharged from the transformers normally into the hoppers shown in Fig. 13, but can by means of a three-way valve be discharged directly into the drain pipe.

The secondary of each transformer is connected to the 2300-volt busbars, which are carried along the side of the building to the feeder switches. These switches are attached to the wall of the building and in front of them are set the controlling and instrument panels, ample working space being left between.

As will be seen, the building is arranged to admit readily of extension should the demands of the service require it, all that is necessary being to extend the side walls and roof and move the end back, no changes being necessary in the front.

For the protection of the transformers some special devices have been employed.

To prevent damage, if for any reason the supply of water should fail and the low water alarm in the tank fail to act or receive the necessary attention, a little device which is called a "water relay" is provided. This piece of apparatus, shown in Fig. 14, and as installed, in Fig. 13, consists of a beam having at one end a small bucket and at the other a balance weight which can be moved along the beam. The beam is fulcrumed so that when the bucket is full of water the combined weight of bucket and water overcomes the balance weight and raises it. A vertical rod attached to the beam moves in a vertical

plane and by means of a system of levers causes two metallic points connected electrically as well as mechanically to dip into two cups of mercury. A small hole is made in the bucket through which the water can be drained out, and two binding posts connected to the mercury cups allow for conveniently attaching the wires of the control circuit. This apparatus is mounted on the discharge pipe over the hopper and the water as it comes from the transformers falls into the bucket. This keeps closed the control circuit of which the mercury cups and contacts form a part. If for any reason the water should cease to flow through the cooling coils there would be nothing to keep the bucket supplied, and what water was left in it would run out through the drain hole, thus allowing the balance weight to fall and opening the control circuit at the mercury cups. By varying the size of the drain hole a fairly accurate time element can be introduced. As will be explained later, the opening of the control circuit at the mercury cups trips out the 60,000-volt oil switch, or starts an alarm bell ringing if the switch should fail to open. This apparatus is the result of much experimenting and has now been perfected to such a degree that absolute reliance is placed on it. It has demonstrated its value on several occasions and all water-cooled transformers installed on the system are now equipped with it, those in the substations where there is no constant attendance being arranged to trip out the oil switch, while in the other substations and power houses it calls the attention of the attendant by ringing the alarm bell.

It not infrequently happens that the water supply may be diminished to such an extent as to allow the temperature of the transformer to rise to a dangerous degree and yet prevent the water relay from operating; or an excessive overload may come on without causing the automatic switches to open. In either event the results as far as the transformer is concerned would be disastrous, and to prevent any damage from these causes a thermostat, Fig. 15, provided with suitable binding posts for attaching the wires of the control circuit, is hung in the oil above the windings. This thermostat is made by riveting together two metal strips of different coefficients of expansion and is adjusted so that when the temperature of the oil reaches 65 deg. cent. the control circuit is opened, which, as in the case of the water relay, trips out the 60,000-volt switch or causes the alarm bell to ring.

The control circuit, Fig. 16, is normally closed, is energized

by a secondary generator giving about 6 volts alternating current on the terminals and has in addition to the water relay and thermostats two modified 50-ohm telegraph relays. These relays are in multiple with each other and in series with the water relay and thermostat.

As originally installed, ordinary relays were used, the magnet coils being energized and the armatures held over against the pull of a spring so that the secondary contacts were open. It was found, however, that the constant chattering of the armature due to the alternating current was very hard on the apparatus and made the relays somewhat unreliable. This difficulty was overcome by providing the magnets with two windings of 50 ohms each, one connected in the control circuit and the other connected directly to the generator, the two windings being in opposition to each other. Thus as long as the control circuit remains closed the armature is not attracted, but should this circuit open, the remaining winding energizes the magnet, attracting the armature and closing the relay circuits or the alarm bell and the "auto trip".

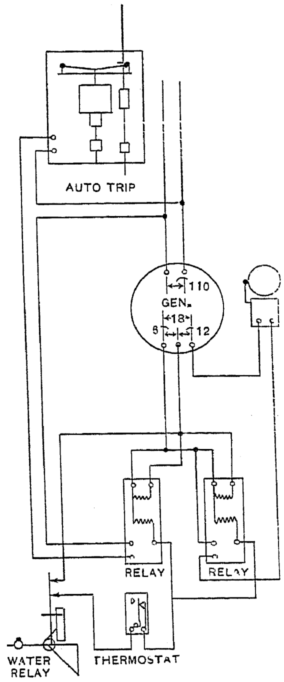

FIG. 16—CONTROL CIRCUIT

The "auto trip", Fig. 17, is a device for tripping the 60,000-volt oil switch. As previously stated, the only relays for this switch are of the series mechanical type, so that no low-voltage connection could be made to them and some other arrangement had to be made.

Between the end of the hand rope which is provided for tripping the switch by hand and the switch tripping mechanism, an iron rod $\frac{1}{4}$ in. (6.3 mm.) in diameter is introduced. This rod, which is connected to the mechanism by a chain, to give flexibility without stretching, passes through the iron box containing the auto trip and at a suitable location has a collar fastened to it by a set-screw. Above the set-screw and surrounding the rod, which can be moved through it freely, is a heavy weight suspended on a dog attached to a toggle arrangement. The trip coil is located under the toggle joint so that

when it is energized the plunger, which has an adjustable dashpot to provide a time element, is pulled up, striking the toggle joint, releasing the weight and allowing it to fall on the collar, which trips the switch. Owing to the iron rod being free to move through the weight, the switch can be tripped by hand at any time, independent of the auto trip.

The substation is provided with a telephone connected to one of the operating lines, the equipment being temporary, to be changed later to a standard equipment. This standard equipment is shown in Fig. 18. The incoming lines connect to the lower ends of the fuses, the telephone being connected to the upper ends. The fuses consist of an alloy wire which fuses at one ampere, contained in glass tubes 14 in. long. Above the telephone connections are the lightning arresters, consisting of two carbon plates separated 0.01 inch by a small sheet of mica with a $\frac{1}{8}$-inch diameter hole in the center, the ground connections being taken from the top of the lightning arresters. As the telephone lines are carried on the same poles with the 60,000-volt line, any trouble on the high-tension system induces high-voltage surges in them which go to ground through the lightning arresters and in most cases blow the fuses. An alarm device is provided which starts a bell ringing should a fuse blow; this is shown below the fuse tubes in Fig. 18. A short pivoted arm carries on one end a contact for the alarm circuit and on the other a small weight. This weight is suspended from the fuse wire by a short piece of fish line so that the alarm circuit is normally kept open, but should a fuse blow, the weight is allowed to fall, closing the contact at the other end of the arm. This alarm device is not generally used in the substations but is always used in the power houses and patrol stations. In the power houses, instead of ringing a bell a small pilot lamp is lit, which indicates at a glance which fuses are blown. In the patrol stations the value of this alarm device is inestimable. Before its introduction there were several occasions on which the fuses were blown during the night and were only discovered when the patrolman awoke in the morning. Under these circumstances it was impossible for the system operator to call the patrolman, but with the introduction of the alarm device this difficulty has been entirely overcome.

The substation is in close proximity to some valuable mine buildings, which are all wooden structures, and fear was expressed by the manager of the mine that if the oil in one of the transformers should catch fire and the burning oil boil

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Name of machine	Number in operation	Size	Length	Diam
West Mill No. 1.				
Jig Motors:				
Rolls....................	3	14 in. x 38 in.	..	.
Water pump...............	1	7 in.	..	.
Elevator.................	1	..	112 ft. 6 in.	.
Jigs.....................	6	4 comp't.	33½ in.	.
Jigs.....................	6	5 comp't	33½ in.	
Trommels.................	4	3 to 10 mm.	10 ft.	48
Elevator.................	1	..	44 ft.	
Table Motors:				
Elevator.................	1	..	84 ft. 6 in.	
Huntington mill..........	2	5 ft.	..	
Sand pumps...............	2	3 in.	..	
Sand pump................	1	2 in.	..	
Frue vanners.............	28	6 ft.	..	
Card tables..............	25	Model C	..	
West Mill No. 2				
Jig Motors:				
Rolls....................	3	14 in. x 36 in.	..	
Elevator.................	1	..	125½ ft.	
Jigs.....................	12	4 comp't	33½ in.	
Jigs.....................	1	3 comp't	33½ in.	
Trommels.................	4	3 to 7 mm.	10 ft.	48
Trommels.................	2	15 mm.	5 ft.	48
Table Motors:				
Chilean mill.............	1	6 ft.	..	
Hardinge "...............	1	6 ft.	..	
Elevator.................	1	..	84 ft. 6 in.	
Frue vanners.............	28	6 ft.	..	
Card tables..............	20	Model C	..	
Water pump...............	1	6 in.	..	
Sand pump................	1	2 in.	..	
Esperanza................	1	..	20 ft.	
Feed Conveyor Motor:				
Feed conveyor............	1	20 in.	451½ ft.	
Rock House				
Storage Bin Motor:				
Conveyor and distributor....	1	..	370 ft.	
Rock House Motor.				
Kennedy crusher..........	2	No. 5	..	
Trommels.................	4	30 mm.	7½ ft.	4
Rolls....................	1	14 in x 36 in.	..	
Conveyor.................	1	..	144 ft.	
"	1	..	140 ft.	
"	1	..	113 ft.	
"	1	..	63 ft.	
Elevators................	1	..	59 ft.	

out of the case it would endanger the buildings. To overcome this objection the building inside is banked with concrete and drains are provided to allow the burning oil to flow into a covered cesspool large enough to hold all the oil in one transformer.

The cost of this substation was as follows:

Building (including concrete foundations and floors)........	$3,733.00
Electrical equipment (exclusive of transformers)...........	5,003.00
Transformers installed..................................	11,125.00
Water system for transformers...........................	651.00
Total..................................	$20,512.00

or $10.52 per kv-a.

The annual cost of operating the substation is as follows:

Depreciation (being the sum of the depreciation of each item and being equal to a little over 7% of the total cost)....	$1,452.00
Interest at 8%..	1,641.00
Taxes..	77.00
Maintenance and operating (being the average of the annual cost since the station was put in service)..............	530.00
Total..................................	$3,700.00

or $1.90 per kv-a.

It should be noted that the small item for operating is due to the fact that the automatic features make it possible to dispense with the services of an attendant. The substation, however, is visited every day by a patrolman who changes the charts of the recording instruments and makes a general inspection.

The maximum demand of the Bunker Hill and Sullivan Company is about 2000 h.p. and Table I shows the connected horse power of motors in the different branches of the mining operations and the percentage of the total.

TABLE I

CONNECTED LOAD OF MOTORS AT BUNKER HILL & SULLIVAN MINE

	h.p.	Per cent of total
Compressors..........................	475	16.1
Mills..........................	965	32.1
Hoists..........................	200	6.7
Pumps..........................	385	13.1
Haulage..........................	438	14.7
Crushers..........................	335	11.2
Other operations..........................	182.5	6.1
	2980.5	100.0

To those who are familiar with the operation of such large mines as the one in question the percentage of motor capacity for driving compressors will no doubt appear small, but this is explained by the fact that a very large part of the air compression is done by water-driven compressors.

The motors in the mills are used for driving a great variety of apparatus and Table II is of interest as showing the different apparatus with the work done by each and the size of motor required. The daily output of the mine is about 1200 tons of ore and there are three mills available to handle it, but Table II merely gives the data of the two newer mills, as the old mill is used only to a very small extent.

The following Table III, which shows the distribution of cost of electric power and light for an average month, is of interest also as showing the cost of this service for the different operations.

TABLE III

DISTRIBUTION OF COST OF ELECTRIC POWER AND LIGHT FOR ONE MONTH

Electric power		Electric light	
Hoist	$218.40	Tramming	$41.10
Pumps	412.80	Hoisting	3.10
Mills	3100.25	Mill	25.40
Mine traction	237.74	Machine shop	0.50
Yard traction	30.40	Saw mill	0.70
Machine shop	11.65	Assay office	0.25
Saw mill	79.10	Blacksmith shop	0.25
Assay office	3.00	Yard	1.10
Compressors	299.10		
Electric light used	72.40		72.40
	$4464.84		

After more than two years' service the results from the operation of this substation have been satisfactory both to the power company and the customer. There have been some interruptions to the service, but considering that the transmission line feeding this station is about eighty miles in length and runs through a rough mountainous country, this has to be expected. During the year 1912 there were fifteen such interruptions of an average duration of fifteen minutes each. The causes were various, such as lightning, limbs of trees blown into the wires, insulators broken by rifle shots and so forth. In addition there were, during the same period, about four interruptions due to trouble on some part of the mining company's installation.

In conclusion the author desires to acknowledge his obligation to Mr. Walter C. Clark, electrical engineer, and Mr. R. S. Handy, mill superintendent, both of the Bunker Hill & Sullivan Mining and Concentrating Company of Kellogg, Idaho; to the former for information given in Table III; to the latter for the information contained in Table II.

DISCUSSION ON "A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT" (FISKEN), VANCOUVER, B. C., SEPTEMBER 11, 1913.

W. V. Hunt: I have listened with great interest to the paper read by Mr. Fisken, and I was particularly interested in the design of a substation that could, if necessary, become a portable substation, inasmuch as it could be moved to another district.

I think in some cases we might go further with the design of substations with that idea in view; we have some substations that are more portable than that, as they are built on standard railroad cars, and we can take them around on our system, and I think this idea might be extended to some mining districts, keeping the capacity of the substation within reasonable limits. We may adopt a substation on the lines of the one developed by Mr. Fisken in some districts adjacent to Vancouver.

Frederick D. Nims: I have talked this subject over with Mr. Fisken considerably during the last year or two, and I think his station and one that we might build would be very much along the same lines; I think there are a few points that we cannot agree upon, one being that he leans a little bit too much to three-phase transformers. In putting in a station such as he describes, with three 650-kw. three-phase transformers, personally I would prefer to put in transformers of a slightly higher voltage, connecting them in delta, having an opportunity of running open delta with one transformer disconnected, if the occasion should arise. This is merely a difference of opinion.

I ask Mr. Fisken to what capacity he thinks it is possible to carry the automatic idea. Personally, I do not see any reason why it should not go as far as you like. Also, from the illustrations, it would appear that a single circuit of 60,000 volts goes into the substation. From what distance does that single circuit run over a double-circuit line, or to what extent is the station dependable on a single circuit, in miles?

I have seen the water relay and it is very ingenious indeed, but the comment which I made to Mr. Fisken is, that I think he has gone a little bit too much to automatic devices and not left quite enough to the man who goes around to look after the station.

W. Fraser: I believe that the use of portable substations or semiportable substations will become more usual in the future than it has been in the past. The cost of operation is actually reduced and I think that is what all companies are trying to accomplish at the present time.

Mr. Fisken did not give us the type of the lightning arrester, nor state whether they are charged bi-weekly or daily; I expect it is daily charging, however, because it seems that a patrolman is on the scene, and therefore it might be convenient to charge them daily.

It hink the advantages of the daily over the bi-weekly charging warrant the installation of the daily charging arrester.

C. F. Terrell: I rather question the use of water-cooled transformers for this class of service; the use of self-cooled transformers means a higher first cost, but on the other hand gives greater simplicity and reliability, freedom from troubles that attend equipment for supplying cooling water, and it would probably be possible to have the substation inspected by the patrolman at less frequent intervals.

L. G. Robinson: The improvement of the automatic substation is undoubtedly going to be a great boon to the railway men who have the electrification of trunk lines at heart.

A great deal of fault was found with the high cost of electrification of trunk lines, and a good deal of that high cost is due to the permanent nature of the substations which have to be built for the purpose. Many features were responsible for this high cost of permanent stations, and principally among them were the idea of continuous service and substantial construction for the high factor of safety recommended by Prof. Karapetoff—a high factor of safety of course is always accompanied by heavy and expensive construction—and I think we can all admit that a high factor of safety in regard to automatic substations can be attained with the acquirement of these automatic features. The station does not have to be built upon heavy lines, of solid concrete; the B. C. Electric Railway Company has succeeded in building a substation which can be carried about on wheels, and Mr. Fisken has succeeded in building a substation which can be moved about at a minimum of expense. Together with this comes the idea of automatically cutting out faulty lines in order that operation may go on uninterrupted. That, I believe, up to the present time has been considered an impossible feat. I know that companies with which I have been connected years before this have operated under great difficulties from this particular feature—they have not been able automatically to cut out high-voltage transmission lines.

I agree with Mr. Nims that a good deal of responsibility should be placed upon the operator, and we must depend upon his " personal equation " so to speak; when the operator finds difficulties there usually is a time element sufficient for him to make up his mind whether he will hang on or cut loose, and that, as a rule, in the past has been the safest procedure—his balancing the cost of interruption against the cost of damage from hanging on.

J. A. Lighthipe: Are you attempting to use telephone transformers between your high-tension line and your telephone? We have in Los Angeles two portable substations of 750 kv-a. capacity, on a heavy 15-ton truck, and we pull this truck all over the country roads, sometimes in the case of emergency with an automobile truck; it has been of the utmost service to us

in helping out some of our substations with burned out transformers. It is also very valuable for conventions and illuminations and things of that sort, where there is for a short time, a week perhaps, a very heavy illuminating load in a certain portion of the town where it is not provided for, except with high potential loads.

A. A. Miller: This matter of automatic substations is attracting an increasing amount of attention. Some of you have undoubtedly read the paper, which was presented by Mr. Summerhayes at a comparatively recent meeting of the Institute, which paper appears in this volume, p. 1685, describing an automatic synchronous converter substation used in the city of Detroit. That station has in it apparatus which is occasionally looked upon as being somewhat difficult to operate, but notwithstanding these difficulties, the automatic starting, synchronizing and adjusting are said to be successfully accomplished, and the synchronous converter made to carry its proper share of the load; all of this being done by means of the single alternating-current circuit provided for supplying power to the substation.

It is reasonable to predict that a somewhat extensive effort will be made to perfect automatic apparatus, and to weed out any defects that may exist, which are only to be discovered by continued use and diversified application, and after the reliability of the equipment and the practicability of the idea are thoroughly established, we can rationally expect considerable use of automatic substations.

There may come a time when such substations will be used in railway trunk line electrification, but the reliability of the assembled parts, working as a whole, must be pretty thoroughly demonstrated before we can expect such application.

Portable railway substations have been successfully used for some years. They involve, in nearly all instances, alternating-current transformers, for reducing to the proper voltage for the rotating equipment required for direct current, generally of 600 volts potential. Sometimes synchronous converters are used in such portable substations, and sometimes motor-generator sets, depending upon the individual preferences of the engineer selecting the equipment and the exigencies of the particular application. I believe that portable alternating-current power substations, both single-phase and polyphase, can be used to great advantage by many power companies. The field for such outfits is surely enlarging rapidly, and the moderate voltage transmission lines, or more properly termed, intermediate voltage distributing lines, are now penetrating many farming and agricultural districts, a class of business not particularly sought heretofore. The result is an increasing number of relatively small substations, the total weight of the apparatus involved being no unwieldy amount. Many of these substations are of the outdoor type, and the form of

construction used makes it possible to provide for easy disconnection of the permanent apparatus, and the quick substitution of a portable equipment. It seems to me this idea is entirely practicable, and that the portable alternating-current substation is bound to become a very handy tool for the power companies.

R. W. Pope: In speaking of the developing of automatic stations and machinery, it occurs to me that a recent law of the state of Washington requiring an additional man at substations might stimulate the invention of automatic devices so that instead of one man there would be no man in attendance.

In visiting a station of this kind attended by one man I happened to glance at the instructions for resuscitation and the name of the nearest doctor to be called, and it occurred to me that, possibly, was one of the reasons why the law was being agitated requiring a second man to be in attendance—in case of the disability of the other one.

The development of the automatic telephone system, I think, is one that might be well studied. Of course the conditions are entirely different. Another instance is the automatic block signals of the railroad companies. The manual system has to a large extent been displaced by the automatic, it having been found that the latter is particularly reliable compared with the attendance of an operator.

R. F. Hayward: The question of the design and operation of transformer substations for large high-tension distribution systems is of very great importance on the Pacific Coast, where wages of operators are very high.

Where operators are employed in transformer stations, it is generally necessary to employ three shifts, and often, as a matter of personal safety, a second man on a shift is employed. If this sort of thing were done for anything but large and important transformer stations, it would run up the operating costs of the distributing system so much that no profitable business could be done in a scattered district.

The time was when current from 2000-volt lines was served to customers through the medium of transformer stations, but now outdoor transformers are in very general use on 12,000-volt distributing systems, which are operating with as much ease and economy as the older 2000-volt systems. Consumers are connected at any point on a 12,000-volt line, through the medium of 12,000-volt transformers placed on poles.

It is only a step from 12,000 or 20,000 volts to distribution at 60,000 volts in much the same manner.

The tendency at the present time is to treat the transformer as part of the line, and if 60,000-volt transformer installations are developed along the lines of Mr. Fisken's design, I do not think it will be very long before a 60,000-volt distribution system can be tapped for service at any point where the demand may occur. The only difference between 60,000-volt and 12,000-

volt installations will be that the units dealt in will be larger in the former than in the latter.

The demand for the supply of power to mines and smelters has been one of the principal causes of the rapid development in long-distance transmission during the past fifteen years. The exacting requirements of the power supply for these purposes have taught operators their most important lessons in giving continuous service.

But of all the lessons learned in the West, the greatest seems to me to be that mechanical strength in line construction, and simplicity of arrangement of switches and connections, will go much further towards continuous service, than duplication of lines, switches and transformers with complicated connections.

Simplicity of connections—whether it be in the generating station, transmission line, or transformer station and distributing lines—is, I believe, the keynote to success in giving continuous service.

V. Karapetoff: This question of delta versus Y connection seems never to lose its interest and it is one of these questions that I do not believe will ever be settled, because the conditions of operation are changing, and the apparatus, the safety, and the reliability desired are also changing with the progress of the art. Personally, I believe that this connection—delta-Y—probably with considerable impedance between the neutral and the ground, is a condition that is applicable to a great many transmission systems, notwithstanding I have found systems that operated delta-delta or Y-Y, and I should like to hear some expression of opinion from those who have the most recent experience as to how the matter stands now.

Mr. Fisken mentions an automatic device for indicating when the fuse wire blows out. Some years ago I was connected with a large transmission company in the East and we had this trouble. Some branch lines on a 60,000-volt circuit were protected by copper fuse wires about 16 ft. (4.8 m.) long, placed in rubber tubes, and at night one of these wires would blow, and a little town or factory would be without light or power and the question was put to me to find some kind of indicator that would notify the nearest patrolman about this occurrence. So I went to the principal manufacturers of this kind of apparatus and suggested all kinds of devices that they could furnish, but one of the representatives finally told me, "You do not need any complicated apparatus, all you need is to attach a weight to your wire so that when it blows the weight drops and closes a circuit that rings a bell in the patrolman's cabin." That was a simple idea, and it did me a great service.

John B. Fisken: Mr. Hunt suggested portable substations on flat cars. I wonder if Mr. Hunt has ever been in a mining district? If we could only get an aeroplane that would lift a 650-kilowatt transformer up to one of our substations it

would be a great help. We have one or two substations where we have as much as 30 or 35 per cent grade to get material up. There is much to be said, however, in favor of the substations on flat cars or on wagons if the country is suitable.

Now, our distribution is not entirely mining. Out of 550 miles (167.6 km.) of 60,000-volt lines, I suppose more than half of it is in farming country with substations scattered all over it, and therefore there is no doubt that the flat car substation might be a very good adjunct to our business; the unfortunate part of it is that the "pickings" are awfully thin. In order to make anything at all we have got to keep down our investment; and when we make our rates we have it understood that we will do the best we can to give a constant service, but we cannot undertake to keep spare transformers in every station, or even go to the expense of maintaining a substation on a flat car. We do keep spare transformers at important points ready for shipment, and we can load a transformer and easily have it started on the road in about two to three hours.

Referring to Mr. Nim's discussion, I do not see any reason why we should go to the expense of hauling three transformers up a mountain side when we can haul one. The weight per kv-a. of three transformers is greater, the space required for them is greater, and when you have to excavate in a mountain side to get some place to set them so they won't roll to the bottom that is quite an item. There is one advantage that Mr. Nims points out, that is, in the event of a burn-out in one transformer, if your connections are delta-delta you can cut out one and run open delta. The three single-phase transformers have six points of weakness—they have six entrance bushings; the three-phase transformer has three, which cuts down the liability of trouble to that extent; but the prime reason why we adopted the three-phase transformer was that our first 60,000-volt line was built into this mining country. Twelve years ago we did not know anything about it, we had nothing to guide us, and the factory engineers recommended three-phase transformers; we took their advice and after ten years of operating experience we have never seen any reason for changing our plans. Where we have three three-phase transformers, we might substitute three single-phase transformers, but we use these three-phase transformers in all our stations, and in many places we only have one transformer, which would mean, if we used single-phase transformers in these stations, that our other spare apparatus would not be available.

Mr. Nims asked the question as to what extent the automatic idea could be carried. My opinion is that there is no limit, it can be carried to almost any extent.

Another question was about the length of the single circuit. This station is 400 ft. (121.9 m.) distant from the main lines, which are in duplicate. The two lines, up to a certain point, follow different routes, on different rights-of-way; at a point

about twelve miles from this particular substation they come together. At that point we have a 60,000-volt switching station, equipped with oil switches, electrically controlled. There we can, by putting the two lines on the same bus at one of our stations, switch the load from one line to the other in case of repairs, which we do frequently. In case of trouble of course we can either switch at this particular switching station or we can transfer the branch line by means of the air switches to either of the main lines. At a point some twelve miles beyond we have another 60,000-volt switching station of oil switches, so that we have considerable flexibility. The duplicate line has not been used to any extent except for repairs. The question of the length of a shut-down in the mines, provided it does not extend over a long period, is immaterial. A large part of the load is in the concentrators. If the power goes off, the concentrator is choked and it has to be cleaned out and started over again, so that the question of whether it is off for 15 minutes or two hours is not very material; the big loss to the mining company is in getting started again.

Mr. Nims suggested that there is too much left to the automatic features, and not enough to the attendant. I do not know whether this contention is right or not, but the attendant claims that he has too much to do; he has to take care of a line that rises to an elevation of about 3000 ft. (914 m.) above where his station is located—there is no road, but there is a rough trail, and he has to go up there five miles (8 km.) very frequently; he has another line about 8 miles in length to take care of, and a third line about the same length, so that the attendant is very seldom at the station. His house is only a few hundred feet away, so that when he is at home he is available; but the station is designed to do without even this attendance; all that we require of him is, as I have said, to change the charts on the recording instruments and make a general inspection of the plant. I think, for that reason, all the automatic features I have outlined are necessary. I might state that in the early days what really started us on working out these automatic features was an occurrence that happened at this same plant, although at that time it was an old substation. I got a call one Sunday morning about six o'clock, telling me the transformer 275 kv-a. at Bunker Hill was burned out. I had just time to jump into some clothes, make a rush and catch the morning train. I reached there about one o'clock and was met by one of the men, who said it was all right. He said "The water stopped running and the transformer got hot." I went down and looked it over, everything was all right; but that was the time when it occurred to me that it was necessary for us to have some means of protecting our transformers in case of a recurrence of a shortage of water, and the "auto trip" or "water relay" was the result. The first water relay we built was a very crude affair, which has gone through a number of stages before we finally adopted our present type.

In answer to Mr. Fraser I would state that the lightning arresters are of the electrolytic type, and are charged daily. The patrolman usually gets back home at night; if he does not he telephones in to one of the mining company's men to charge the arresters; but as a rule he attends to them himself.

Mr. Terrell questioned the use of the water-cooled transformers, and his contention I think rather well founded. Unless there is a water supply under gravity, I do not favor the use of water-cooled transformers, and in our practise we are getting away from them. Our first transformers used in the Coeur d'Alene country were all water-cooled. Our experience now is that up there it is the hardest thing in the world to get water. The mining companies actually pump the water for the concentrators two or three times; after the water has gone through the mill they catch it and pump it up again, so that we have been compelled on that account to get away very largely from the water-cooled transformers; but whenever a supply of good water under pressure can be obtained the saving in the cost of handling a water-cooled transformer as against an air-cooled certainly justifies the use of the water-cooled transformer, especially where you have to haul them up the side of a mountain.

Mr. Robinson suggested automatic substations for railway electrification. If you gentlemen ever come to Spokane, and I hope some day you all will, you will have an opportunity of seeing automatic substations on an electric railroad. The Inland Empire Railway system covers about 100 miles (161 km.) of single-phase railway where the substations are entirely automatic. I am not very familiar with the apparatus there, but I do know that I have never seen any attendant. As a general thing substations are located close to a depot, and the agents, when they are not telegraphing or making out waybills or doing something else, go across and look at them; they have worked out the automatic substation for railway electrification.

In regard to our chairman's question, we are using many telephone transformers. Our incoming telephone lines to the Spokane office—we have six or eight of them—are all equipped with telephone transformers; the main generating plants are equipped with telephone transformers; on such substations as I have outlined we provide a stool, which is nothing more or less than a high-tension insulator with a platform on top of it, and a man stands on that when he is telephoning.

I think I have answered our chairman's remarks with reference to a substation on a truck, in talking on Mr. Hunt's remarks.

Mr. Pope is laboring under a misapprehension; the Washington code does not require two men in each station, although it is true that a bill was introduced at Olympia last winter calling for two men. The reason, so far as I know, for requiring two men in each station had no reference to safety; it was simply to make jobs. Mr. Hayward touched on the question of two

operators in a station. We have one station in Spokane, which is our high-tension substation where our lines come in from our outside plants. At that station we have one operator on shift only, and the other operator is in his house (they both live in cottages provided for them alongside the substation) so that if help is required and the operator on duty is able to go for the help he can get it. There is no reason why he should ever have any trouble so far as the electrical arrangements are concerned, as that station is made about as "fool-proof" as it can be made. The switches are all remote control, and the disconnecting switches are handled with long insulated rods, and the only case where he might require help would be in case he should faint or be taken sick; so far as any question of electrical risk is concerned that is practically eliminated. Mr. Hayward's remarks with reference to the reliability of service over one line I think are well taken. We supplied the Coeur d'Alene country from 1903-1908, I believe it was, on one line. We went in there when all the developed mines were running either on water power or on steam; since the day we started giving service I do not believe there has been one single piece of steam apparatus going into that district. The few steam plants that they had, if they are not in the junk pile, are ready to go; the water power of course they use, because that saves them a little money, but very little; so I think we have demonstrated that you can give service over one line that will satisfy a mining community. I am very glad indeed to know that Mr. Hayward endorses my views on the three-phase versus the single-phase transformers.

I am going to dodge Prof. Karapetoff's suggestion of taking up the question of delta versus Y, it is too big; we could argue all day and never get any result. I will say this, that our prime reason for adopting Y on the high-tension side is the fact that we reduce our strains on all the apparatus by grounding our neutral at the generating plants. We have a stress due to 34,700 volts from line to ground. I believe that that is worth a whole lot, and of course doing that prevents a delta-delta connection. We do not use any resistance in our ground connection. We started ten years ago with grounds all through our system; experience has rather tended to indicate that is wrong, and we are now removing the grounds everywhere except at the power plant; at the power plant we expect to keep our grounds, and we expect to have them dead grounds without any resistance; if a line is in trouble the sooner we know it the better, because we can get out and fix it.

I was very much interested in Prof. Karapetoff's statement about the visit to the manufacturer who told him how to arrange his telephone lines to give the indication in case of fuse blowing. I wish I had known that manufacturer, because it would have saved us a whole lot of worry.

The rate for power in the Coeur d'Alene district is $3 per

kv-a. per month, based upon the maximum kilovolt-amperes used in each month, and in addition a charge of one-half cent per kilowatt hour for the kilowatt-hours used in each month. For a one-year contract there is no discount; two-year contract 10 per cent; three-year contract 15 per cent; five-year contract 25 per cent; the Bunker Hill & Sullivan Concentrating Company is working on a five-year contract, so from that the rate can be figured.

J. A. Lighthipe: What is the length of time required to install an oil transformer, to replace the burned-out one; that is, to dry out and fill with oil? You spoke of the kv-a. capacity. What capacity charge is taken for them on the kv-a. or the kilowatt capacity?

J. B. Fisken: We take the assumed voltage of 2300 and measure the amperes. As to the time required to change the transformer in the case of a burn-out, it is a little hard to answer because it depends altogether on where the burn-out is. In our more improved substations we have spare transformers. Now, in the Coeur d'Alene country we can get one into service in about three hours.

A paper presented at the 286th Meeting of the American Institute of Electrical Engineers, New York, October 10, 1913.

TUNGSTEN LAMPS OF HIGH EFFICIENCY—I

Blackening of Tungsten Lamps and Methods of Preventing It

BY IRVING LANGMUIR

While the transformation of electrical energy into heat or even into mechanical energy has for many years been accomplished with efficiencies well above 90 per cent, the artificial production of light has been notoriously inefficient.

The first carbon incandescent lamps had a specific consumption of five to six watts per mean horizontal candle, but these were gradually improved over a long period of years to about 3.1 watts per candle, until finally by the use of the metallized filament a specific consumption of 2.5 watts per candle was reached commercially. Since the introduction of the metallized carbon filament, progress with other types of lamps has been comparatively rapid, and at the present time the most efficient commercial incandescent lamp, the lamp with a tungsten filament, has a specific consumption of from one to one and a quarter watts per candle in the ordinary sizes.

Notwithstanding this decided improvement, we are still far from the theoretical maximum of efficiency that would be attained if all the energy of an electric circuit were converted into visible light.

Drysdale (*Proc. Roy. Soc.* 80, 19 (1908)) has given for the specific consumption of a source of white light of perfect efficiency the value 0.10 watt per candle, and for a source of monochromatic yellow-green light the value 0.06 watt per candle. Ives (*Astrophysical Journal* 36, 322 (1912)), however, gives values very much lower than this; namely, 0.012 watt per candle (800 lumens per watt) for yellow-green light.

The luminous efficiency of the ordinary tun[illegible] therefore somewhere between 1 and 6 per cent.

It is well known that tungsten lamps can be r[illegible] much higher than their rated voltage, and that i[illegible] tremely high efficiencies may be obtained, but t[illegible] lamps run under these conditions is so short that cost of renewals more than offsets the saving in el[illegible] It is readily seen that the limit of the commerci[illegible] tungsten lamps is therefore not determined by the of the tungsten. In fact, if the temperature of the fi[illegible] to the melting-point, the specific consumption for [illegible] seconds may be as low as 0.20 watt per mean hori[illegible]

The causes which have made it necessary to o[illegible] lamps at such relatively low efficiencies as that to one watt per candle have been little u[illegible] seemed, therefore, that an investigation of t[illegible] occurring in tungsten lamps, carried out w[illegible] reaching a clear understanding of the causes [illegible] of the lamps, might possibly open the way t[illegible] of methods by which the efficiency could be gr[illegible]

The present paper is a description of some ex[illegible] theoretical work, extending over a period of ma[illegible] has now resulted in the production of a new t[illegible] lamp; a lamp which will give a life of more than [illegible] specific consumption in the neighborhood of 0.50 [illegible]

INVESTIGATION OF CAUSE OF FAILURE [illegible] TUNGSTEN LAMPS

Ordinary tungsten lamps fail, in general, in o[illegible] namely, either by breakage of the filament, or [illegible] the bulb. In ordinary practise the useful life [illegible] considered to be the time which the lamp burns [illegible] power has fallen to 80 per cent of its original va[illegible] filament breaks, in case this occurs while the [illegible] still above 80 per cent.

The breakage of the filament was a very seri[illegible] early tungsten lamps, as the filament material [illegible] brittle. This difficulty has now been overcom[illegible] tion of ductile tungsten wire* and by better meth[illegible] the wire in the bulbs, so that lamps can now be [illegible]

*Coolidge, TRANS. A. I. E. E. Vol. XXIX, p. 961 [illegible]
Fink, Trans. Amer. Electrochemical Soc. 17, 229, [illegible]

so strong that a blow is more likely to break the bulb than the filament.

The life of ordinary tungsten lamps, except those of low wattage (40 watts and less), is at present practically determined by the rate at which the candle power decreases. The main cause of this decrease is evident by mere inspection of a lamp which has run several hundred hours. It is due simply to the blackening of the inner surface of the bulb. It is true that the candle power of the filament itself changes somewhat during its life, but this change, on the whole, is an increase in candle power, rather than a decrease. Careful measurements show that during the first few hours running there is usually a slight increase in candle power owing to some change in the surface of the filament which causes greater emissivity of light, or to a slight increase in the conductivity of the filament which leads to an increase of the current and therefore a higher filament temperature. On the other hand there is a tendency towards a lowering of the candle power during the latter part of the life owing to the decreasing diameter and consequent fall in temperature of the filament. Both these causes are insignificant in their effect, as compared with the blackening of the bulb.

The reason for the limited life of the larger sizes of tungsten lamps when run at a specific consumption of one watt per candle, and therefore the reason that higher efficiencies could not be obtained in practise, was evidently the blackening of the bulb.

The cause of this blackening was the subject of much speculation. The prevalent opinion seemed to be that in a normally operated lamp it was due to disintegration of the filament, caused by the presence of traces of residual gas, whereas in lamps run at much more than their rated voltage it was perhaps caused by evaporation. Others, however, considered it due to leakage currents of electricity (Edison effect) across the space between the positive and negative end of the filament. It is well known that discharges through gases at low pressures, cause a marked disintegration of the cathodes. Still others were of the opinion that the blackening of the bulb was due primarily to evaporation of the filament.

In the manufacture of carbon incandescent lamps, it had been found necessary to use a relatively high vacuum, as otherwise the lamps were found to have a very short life. That is, the bulbs blackened rapidly or discharges occurred between the two ends of the filament, finally resulting in the formation of an arc which destroyed the lamp. Various attempts had been made

to prevent the blackening by the introduction of gases at various pressures in the lamp. For example, Edison (U. S. Patent 274,295, March 20, 1883) proposed introducing nitrogen or cyanogen at relatively high pressures, into lamp bulbs, for the purpose of preventing the electric discharge between the positive and the negative end of the filament. In this way he hoped to prevent blackening. These attempts, however, were completely unsuccessful, and it can be readily shown in the case of a carbon lamp, run at say 3 watts per candle and containing nitrogen at atmospheric pressure, that the filament loses weight more rapidly than when run in a vacuum at the same specific consumption. Similar experiments with cyanogen, or even cyanogen mixed with nitrogen, always give lamps which, when run at $3\frac{1}{2}$ watts per candle, give a much shorter life than that of similar lamps with evacuated bulbs run at the same specific consumption.

At a later date, in order to account for this failure to obtain good lamps without a vacuum, the theory was advanced that the presence of a chemically inert gas in a lamp caused a rapid disintegration of the filament by a mechanical " washing," the idea presumably being that the rapid motion of the gas molecules striking against the surface of the filament caused a disintegration of the filament. The general experience of those engaged in the manufacture of lamps did not bear out this theory and it was therefore gradually superseded by others in which the disintegration of the filament was considered to be due to chemical or electrical action of residual gases, rather than to simple mechanical "washing."

In the commercial production of lamps it was found necessary at first to use mercury pumps for the exhaustion of the lamps; mechanical pumps were not good enough. Later it was found possible to obtain a sufficiently good vacuum with mechanical pumps, which by that time had been considerably improved, by introducing red phosphorus into the stems of the lamps and by volatilizing this phosphorus into the lamp just before sealing off, and at the same time heating the filament to a much higher temperature than that at which it was to run normally. It should be pointed out that not only was it necessary to use some such special method of exhaust, but in order to obtain lamps of good life, the bulbs themselves had to be heated to a high temperature during the exhaust, in order to drive off any gases condensed on the surface of the glass. It is interesting to notice that the lamp manufacturers had adopted these precautions in obtaining a high vacuum long

before the necessity for them was realized by most scientific investigators engaged in work with high vacuum.

When the lamp factories began the manufacture of tungsten lamps, they found that much greater precautions were needed in the exhaustion of these lamps than had been necessary for the ordinary carbon lamps, and many improvements in the methods of exhaustion were adopted.

Unless all this care was taken to obtain the best possible vacuum, there were striking evidences of the presence of residual gas in the lamps after they were sealed off. For example, if the normal voltage of the lamp was suddenly applied, a flash of blue glow appeared. Gradually, after a few flashes, this discharge would disappear. This was taken to indicate that the vacuum had been "cleaned up" by the discharge. A similar action of an electric discharge is known in Geissler tubes and X-ray tubes.

In carelessly exhausted lamps, the blue glow would often persist, gradually getting worse, until the lamp "arced across," destroying the filament.

The effect of a poor exhaust was thus to cause the lamps to arc across during the aging process, or to cause them to blacken prematurely.

The general factory experience thus confirmed the opinion that the blackening of the bulb was due primarily to minute traces of residual gas, or to electrical discharges within the lamp.

Much evidence had also gradually accumulated in this laboratory showing that even remarkably low pressures of gases often produced very rapid blackening of the bulbs. A brief account of the early work along these lines has been presented before this Institute by Dr. W. R. Whitney (Trans. A. I. E. E., Vol. XXXI, p. 921, 1912).

Various attempts to improve the life of lamps by obtaining a better vacuum than usual, had not been very successful. This failure, however, could not be taken as proof that a better vacuum would not improve the life. In the first place, it had been found that during the running of the lamp the vacuum gradually improved after sealing off ("clean-up" effect), the pressure finally reaching a value probably lower than that directly obtainable by any of the well known methods of exhausting. Yet even where we had pressures lower than would be indicated by the most sensitive vacuum gages, we often had clear indications that the blackening of the bulb was due to imperfect exhaust. It seemed quite possible,

therefore, that there might remain, in lamps, minute traces of some gas or vapor which we had not yet learned to remove by our usual methods of exhaust. This residual gas might easily be the cause of the gradual blackening of the bulbs.

Since the pressures were too low to measure, we had no way of knowing definitely whether one method of exhaust was better than another, so that any failure to improve the life by a new method of exhaust might simply mean that the vacuum had not been improved.

It seemed, therefore, that the question as to whether a better vacuum would give a better lamp could only be settled by a direct investigation of the cause of the blackening.

Two lines of attack were decided upon:

1. Study of the sources of gas within a lamp.
2. Effects produced in lamps by various gases.

To facilitate this work, an elaborate piece of vacuum apparatus was built consisting of an improved form of Töpler (mercury) pump, a sensitive McLeod gage and a vacuum oven in which lamps could be heated and exhausted without being subjected to atmospheric pressure from without. Provision was made for the introduction at will of small quantities of any gas to the lamp. Special apparatus was devised by which gas analyses could be made with extremely small quantities of gas evolved within the lamp. For example, it is possible with this apparatus to make a quantitative chemical analysis of a single cubic millimeter of gas and determine the following constituents: oxygen, nitrogen, hydrogen, carbon dioxide, carbon monoxide and argon.*

Sources of Gas within the Lamp

There are four sources of gas within the lamp bulb: first, residual gas left by evacuation; second, gas given off by the filament; third, gas from the lead-in wires or the anchors; and fourth, the gas given off by the glass.

1. *Residual Gas*. The mechanical pumps ordinarily used in exhausting lamps produce a vacuum of about 0.001 mm., according to the McLeod gage. This is probably about the pressure of the non-condensible gases left in the lamp. Besides this, however, there must be some water vapor and oil vapor, and if the filament has been lighted during the exhaust, as is usually the case, there will be some carbon monoxide, carbon dioxide, and

*For a brief description of this apparatus and the methods of analysis employed, see *Journal American Chemical Society*, Vol. 34, 1912, pp. 1310 and 1313.

hydrogen produced by the action of the filament on the vapors. Probably most of these gases are nearly completely removed, or precipitated on the walls of the bulb, by the clean-up that occurs when the phosphorus is volatilized into the lamp and a blue glow made to occur. The final pressure, just after sealing off, is usually in the neighborhood of 0.001 mm. or less.

2. *Gas from the Filament.* The prevalent opinion, as expressed generally in scientific literature, is that metals when heated to very high temperature in vacuum, evolve very large quantities of gas. For example, in a recent article, Prof. J. J. Thomson (*Nature*, 91, p. 335, 1913) says: "Belloc, who has recently published (*Ann. de Chimie et de Physique* (8) 18, p. 569) some interesting experiments on this subject, after spending about six months in a fruitless attempt to get a piece of iron in a state in which it would no longer give off gas when heated, came to the conclusion that, for practical purposes, a piece of iron must be regarded as an inexhaustible reservoir of gas." Thomson's own experience is quite similar.

That the effect of the presence of gas in the metal is considered of importance in connection with the disintegration, is evident from the following quotations from J. J. Thomson's book on "Conduction of Electricity through Gases" (1906 edition). On page 215, he says: "The facts just mentioned suggest that the gas absorbed by the platinum and slowly given off when heated plays an important part in the carriage of the electricity from the wire."—"The emission of absorbed gas from the platinum is, however, according to Berliner (*Wied. Ann.* 33, p. 289, 1888), closely connected with the disintegration of the platinum wire which takes place when the wire is kept glowing and which is made evident by a deposit of platinum or platinum oxide on the walls of the tube and a diminution in the weight of the hot wire: the carriers of the electricity might thus be the dust or vapor of platinum escaping from the wire." Then, on page 216: "There is thus a close similarity between the laws of disintegration of the wire and those of the leak of positive electricity from it."

On page 550, in speaking of the gases given out by the cathodes of vacuum discharge tubes, he says, in discussing some work of Skinner (*Phys. Rev.* 21, p.1, 1905): "The amount of hydrogen that can be got out of a cathode in this way is very large; thus, from a silver electrode 0.15 cu. cm. in volume, Skinner obtained about 2 cu. cm. of hydrogen at atmospheric pressure,

without any indication that the supply was in any way exhausted."

The first few experiments (see *Jour. Amer. Chem. Soc.* 35, 105, 1912) on the gases evolved from the filament of a tungsten lamp also seemed to show the presence of inexhaustible supplies of gas within the filament. Later work proved, however, that this gas was not actually evolved from the filament, but was produced from the decomposition by the filament of water vapor or hydrocarbon vapors present at extremely low pressure in the bulbs. It was finally found that with small filaments, such as are used in lamps, the gas evolved by heating is not more than from three to ten times the volume of the filament. By thoroughly cleaning the surface of the wire before heating, the amount of gas is usually not over half as great. The surprising fact was observed that at least 90 per cent of the gas was given off within a few seconds on first heating the wire to a temperature exceeding 1500 deg. cent. At a temperature below 1200 deg., however, the gas is given off only very slowly, if at all. The gas consists of about 70 to 80 per cent carbon monoxide, the remainder being mostly hydrogen and carbon dioxide. The total amount of gas evolved from the filament of a 40-watt lamp, if liberated in the lamp after sealing off, would produce a pressure of from 0.006 to 0.02 mm.

3. *Gas from Lead-in Wires and Anchors.* In many of the larger lamps, where the leads or anchors become very hot, there are often clear indications that the gas evolved from this source has a marked effect on the life, particularly on the tendency to arc across during aging. In the experimental lamps made with small sizes of wire, the quantities of gas obtained from this source were found to be too small to measure.

4. *Gas from the Bulb.* On heating bulbs of 40-watt lamps (volume about 250. cu. cm.) for three hours to a temperature of 200 deg. cent., after having dried out the bulbs at room temperature for 24 hours by exposure in a good vacuum to a tube immersed in liquid air, the following average quantities of gas were given off:

200 cu. mm. water vapor
5 cu. mm. carbon dioxide
2 cu. mm. nitrogen.

These are the quantities of gas, liberated by the heating, expressed in cubic millimeters at room temperature and atmospheric pressure.

By raising the temperature of the bulbs from 200 deg. to

350 deg., an additional quantity of water vapor was obtained, so that the total now became

300 cu. mm. water vapor
20 cu. mm. carbon dioxide
4 cu. mm. nitrogen.

A subsequent heating of the bulbs to 500 deg. cent. caused the total amount of gas evolved to increase up to

450 cu. mm. water vapor
30 cu. mm. carbon dioxide
5 cu. mm. nitrogen.

At each temperature the gas stopped coming off the glass after a half hour of heating, only to begin again whenever the temperature was raised to a higher value than that to which the bulb had been previously heated.

It therefore seems that even by heating the bulb to 500 deg., not all of the water vapor can be removed, but it does seem probable that after this treatment the amount of water vapor that can come off a bulb at ordinary temperatures must be extremely small.

This study of the origin of the gases within a lamp thus led to the following important conclusion:

The amounts of residual gas, together with all the gas that is given off by the filament and its supports, are quite insignificant as compared with the gas on the inner surface of the bulb. Furthermore, the great difficulty of completely removing the gases from the glass makes this source particularly troublesome in incandescent lamps. We see that the gases likely to be present or given off in an exhausted lamp are, in the probable order of their importance: water vapor, carbon dioxide, hydrocarbon vapors, hydrogen, carbon monoxide, nitrogen and, when phosphorus is used, various phosphorus compounds.

Effects Produced in Lamps by Various Gases

Small quantities (up to 0.1 mm. pressure) of various gases were let into lamps sealed to the special exhausting system and their behavior during the operation of the lamps was noted. The phenomena observed were extremely varied in character, each gas producing very specific effects. In all cases (except argon) a marked clean-up of gas occurred under proper conditions. These effects have been studied in great detail and are forming the basis for a series of publications from this laboratory on chemical reactions at very low pressures. In the present paper only a very brief outline of the results will be given.

*Hydrogen.** This gas cleans up (disappears) in a lamp bulb in four distinct ways. Relatively large quantities (20 to 50 cubic mm.) of hydrogen are driven on to the bulb when the filament is at relatively low temperature (1500 deg. or more). This hydrogen is particularly active chemically (atomic hydrogen) and will react even at room temperature with many reducible substances. Moderate heating of the bulb will cause a large part of it to escape from the glass again. Since water vapor in the bulb is decomposed by the filament to form hydrogen and an oxide of tungsten, there is nearly always a considerable amount of active hydrogen stored up on the bulb after the lamp has been running some time.

The amount of heat carried away from a filament by hydrogen at low pressures, say 0.001 mm., although many times greater than with any other gas, was found to be entirely negligible compared with the heat radiated from the filament. The cooling effect of such pressures of gas, therefore, has no appreciable effect on the life of lamps.

Dry hydrogen in lamps was never found to have the slightest tendency to produce blackening of the bulbs. That is, the bulbs never blackened more rapidly than if the filament were run at the same temperature in a vacuum. Subsequent experiments have proved that this is true from low pressures up to atmospheric pressure.

Oxygen.† At all temperature above 1000 deg. this gas reacts with tungsten to form the yellow oxide WO_3, no matter how low the pressure of the oxygen may be. The oxide distills off the filament and deposits on the bulb, but owing to its light color the deposit is invisible when the amount of oxygen is less than 100 to 200 cu. mm. Oxygen therefore never produces blackening of the bulb.

Nitrogen.‡ There are three ways in which this gas cleans up in a lamp, each being an exceptionally interesting phenomenon in itself. With voltages above 40 volts and pressures above 0.001 mm. the nitrogen cleans up, provided the filament temperature exceeds 2000 deg., and causes an attack on the negative end of the filament, producing a brown deposit of tungsten nitride, WN_2, on the bulb. Except where the amount of nitrogen that cleans up is much larger than could possibly be present in an ordinary lamp, this gas never causes any discoloration of the bulb.

*See Langmuir, *Jour. Amer. Chem. Soc.* 34, 1310, (1912).

†Langmuir, *Jour. Amer. Chem. Soc.* 35, 105 (1913)

‡Langmuir, *Jour. Amer. Chem. Soc.*, 35, 931, (1913).

Carbon Monoxide. This gas behaves almost exactly like nitrogen. At low pressures it never produces perceptible blackening of the bulb, although at higher pressures it may slowly give a slight deposit of carbon under certain conditions. The results, however, clearly indicated that traces of carbon monoxide such as might exist in lamps, could not be responsible for the blackening.

Carbon Dioxide. This gas attacks the filament and produces carbon monoxide and an oxide of tungsten, without producing any perceptible blackening.

Water Vapor. Even very low pressures of water vapor react with the tungsten filament in a lamp to produce hydrogen, and cause rapid blackening of the bulb. Thus a lamp made up with a side tube containing a little water which is kept cooled by a freezing mixture of solid carbon dioxide and acetone (−78 deg. cent.) will blacken very rapidly when running at normal efficiency, although the vapor pressure of water at this temperature is only about 0.0004 mm.

The fact that lamps exhausted at low temperature (say 100 to 200 deg.) blacken so rapidly during life, together with the fact that water vapor is the principal gas removed from the bulb by heating, indicate that the water vapor is responsible for the short life under these conditions.

It is rather surprising that water vapor should have such a marked effect when either of its constituents, hydrogen or oxygen, acting alone, produces no blackening.

The explanation of the behavior of the water vapor seems to be as follows:

The water vapor coming into contact with the filament is decomposed, the oxygen combining with the tungsten and the hydrogen being evolved. The oxide distills to the bulb, where it is subsequently reduced to metallic tungsten by atomic hydrogen given off by the filament, water vapor being simultaneously produced. The action can thus repeat itself indefinitely with a limited quantity of water vapor.

Several experiments indicated that the amount of tungsten that was carried from the filament to the bulb was often many times greater than the chemical equivalent of the hydrogen produced, so the deposit on the bulb could not well be formed by the simple attack on the filament by water vapor.

Another experiment demonstrated that even the yellow oxide, WO_3, could be reduced at room temperature by atomic hydrogen. A filament was heated in a well-exhausted bulb containing a low

pressure of oxygen; this gave an invisible deposit of the yellow oxide on the bulb. The remaining oxygen was pumped out and dry hydrogen was admitted. The filament was now lighted to a temperature (2000 deg. K)* so low that it could not possibly produce blackening under ordinary conditions. In a short time the bulb became distinctly dark, thus indicating a reduction of the oxide by the active hydrogen. Further treatment in hydrogen failed to produce any further darkening, showing that the oxide could only be reduced superficially.

Methane. This gas was decomposed, producing hydrogen, while the carbon was taken up by the filament, as was indicated by the resulting change in the electrical resistance. At very high temperatures the carbon distilled out of the filament again. No visible blackening of the bulb occurred in the experiments with methane.

Argon. The behavior of argon was very interesting. Except with high voltages on the filament and very low pressures of argon, no clean-up of this gas could be observed, even on heating the filament up to its melting-point. The slight clean-up which was observed at high voltages was limited in amount. All of the gas which did disappear could be recovered by heating the bulb.

The presence of argon at pressures above 0.005 mm. and below 1. mm. causes a very large Edison effect and a very rapid blackening of the bulb and attack on the negative end of the filament. The deposit occurs mostly behind the anode, showing that the tungsten atoms in this case are negatively charged.

Although these pressures of argon may cause serious blackening of bulbs, yet the experiments indicated that this is not ordinarily the cause of blackening in well-exhausted lamps. The amount of blackening seemed to depend primarily on the Edison effect caused by the argon, rather than the presence of the gas itself. As the pressure was decreased, the Edison effect decreased even more rapidly, and apparently disappeared entirely, long before a degree of vacuum was reached which could readily be obtained with the pump. It seems extremely improbable that the amounts of argon which might exist in an ordinary lamp could perceptibly affect the Edison current or the rate of blackening.

Higher pressures of argon, close to atmospheric pressure, do not cause either Edison effect or blackening.

*The letter *K* is used to denote temperatures on the Kelvin scale, (absolute temperatures).

Effects of Other Gases. Many other gases and vapors, such as chlorine, bromine, iodine, sulfur, phosphorus, phosphine, hydrochloric acid, etc., were tried, but in no case did these gases produce blackening of the bulbs. If great care is not taken in these experiments to have the gases extremely dry, very marked blackening will result.

Contrary to earlier experiments, it was found that mercury vapor in a lamp did not cause blackening if the voltage was low enough so that no serious Edison effect occurred.

Attempts to Eliminate Water Vapor

This study of the effects produced by various gases led to the conclusion that if the blackening of bulbs of ordinary lamps was caused by imperfect vacuum, then it must be due to water vapor and the further removal of water vapor would markedly increase the life of the lamps. The problem of improving the efficiency of lamps thus assumed more definite form.

Experiments were next undertaken to detect the presence of water vapor in lamps after they had been exhausted at high temperature. It was found on lighting the filaments of lamps which had been exhausted at 200 deg. and then cooled to room temperature, that there was a steady but slow *apparent* evolution of hydrogen from the filament. However, in some lamps exhausted at 350 deg., there was barely a trace of gas evolved under similar conditions. This evolution of gas served as a measure of the rate at which water vapor diffused off the surface of the glass. It proved unreliable as an accurate measure of the water vapor, because of the clean-up of the resulting hydrogen.

Lamps were next exhausted in the special vacuum oven, so that the temperature of the bulb could be raised during exhaust to a temperature about 100 deg. higher than that otherwise attainable. A good mercury pump was used and care was taken to remove the last traces of mercury vapor, water vapor and carbon dioxide, by placing between the lamp and the pump a trap immersed in liquid air. The lamps were exhausted from one to three hours under these conditions. The filaments were heated to high incandescence to drive off gas. The lamps were sealed off when the pressure by the McLeod gage read about 0.00005 mm. These lamps were put on life test and compared with other lamps made under factory conditions.

The unexpected result of this work was that the life of the lamps exhausted with all these precautions was not materially

better than the *best* of the lamps made regularly in the factory. The life of the lamps could certainly not be improved on the average by more than 20 per cent by such methods.

In order to make sure that traces of water vapor were not evolved from the bulb, under the influence of perhaps radiation from the filament, or some other such cause, some lamps exhausted like those described above were run at an efficiency of about 0.7 watt per candle, with the bulbs completely immersed in liquid air during their entire life. Some similar lamps, exhausted in the same way, were run for comparison with their bulbs at room temperature. A third set was run with the bulbs heated continuously in an oven to about 150 deg. cent. The life of all three sets of lamps was practically identical. Previous tests had shown that lamps exhausted in the ordinary way, when kept at 150 deg. during life, gave a very much shorter life than lamps run at the ordinary temperature. These special methods of exhaust therefore did not improve the life of the lamp above that of an ordinary lamp run under normal conditions, but they did make it possible for a lamp to run with the bulb at a high temperature without serious impairment of its life. This seemed to demonstrate that even the complete removal of water vapor from the lamp bulb would not lead to a very radical improvement in the life of the lamp, although the presence of minute traces of water vapor certainly did cause a marked decrease in the life.

The conclusion to be drawn from all of the foregoing work is that the blackening of the bulbs of ordinary well made and well exhausted lamps is *not* caused by imperfect vacuum.

Among all the causes of the blackening that have been suggested, the only one that remains is evaporation of the filament.

Evaporation of Tungsten

To test out whether or not this was the correct explanation, many experiments were undertaken to determine the rate of loss of weight of tungsten filaments when run at various temperatures in lamps. It was found that in lamps with filaments run at the same temperature the loss in weight was proportional to the surface of the filament and independent of the size of the bulb. The temperature coefficient of the rate of loss of weight was extremely high, as would be expected if it were proportional to the vapor pressure of the metal.

Furthermore, the actual measurements at various temperatures

agreed remarkably well with the rational formula for vapor pressure

$$\log P = A - \frac{B}{T} - C \log T$$

From some simple considerations of the kinetic theory of gases, it has been possible to calculate from these data the actual vapor pressure of tungsten at various temperatures. These results have been published in the *Physical Review* (Vol. 2, p. 329, 1913). It is of interest to give here simply the results at a few temperatures:

Specific consumption watts per candle	Temperature (absolute)	Vapor pressure mm.
1.0	2400 deg. K..	0.000,000,05
0.4	2800	0.000,03
0.2 (melting-point)	3540	0.080
(boiling-point)	5200	760.

Experiments with lamps exhausted at a low temperature have shown that the temperature coefficient of the rate of blackening is much lower than in well exhausted lamps. Thus, lamps exhausted at 100 deg. and run at say 5 watts per candle, often blacken nearly as quickly as similar lamps run at 2 watts per candle, although the rate of evaporation in a good vacuum would be very different. This serves to show clearly the radical difference between the two kinds of blackening.

METHODS OF PREVENTING THE BLACKENING OF BULBS

Having now shown that the blackening of ordinary tungsten lamps is caused by evaporation of the filament, the problem of increasing the efficiency of the lamps becomes a very definite one.

Introduction of Gases at High Pressure. Although in the past it has usually been found that the presence of a high pressure of gas causes an increase in the rate of disintegration of a heated metal,* yet if we know, as we now do in the case of tungsten,

*For example, see a recent paper by J. H. T. Roberts, on "The Disintegration of Metals at High Temperatures," *Phil. Mag.* (6), 25, pp. 260 (1913). He gives evidence that the disintegration of platinum and iridium is due to the formation of a volatile endothermic oxide and not to evaporation. In a future paper the present writer will show that at least in the case of very highly heated platinum in oxygen at pressures as low as 0.1 mm., the rate of loss of weight is due entirely to evaporation and is independent of the pressure of oxygen, although all of the platinum which evaporates from the wire combines with the oxygen to form the oxide PtO_2.

that the phenomenon is simply one of evaporation, then we have every reason to believe that the presence of a chemically inert gas will reduce this evaporation. We have seen that low pressures of gases (except water vapor and argon) do not produce any perceptible blackening of the bulb, and therefore produce no disintegration in the ordinary sense. Most gases react chemically with tungsten at high temperature, but hydrogen, nitrogen, argon, and mercury vapor seem to be chemically inert towards it.

In the manufacture of tungsten filaments it was for a long time the practise to sinter the filament thoroughly by heating it to a high temperature in hydrogen or in a mixture of nitrogen and hydrogen. If care were taken to avoid air or moisture in the "forming gas" the filaments would stand heating for a long time in these gases, which indicated that they were at least relatively chemically inert.

Whether the loss in weight at a given temperature was actually greater or less than in vacuum could not be determined from these rough observations. To test this out, a lamp was made and filled with carefully dried and purified hydrogen at atmospheric pressure. The filament was run at the same temperature as that of lamps running at one watt per candle. The heat lost from the filament by convection was so serious that actually 17 watts per candle were required to maintain the filament at this temperature. This lamp, however, ran for more than 360 hours without showing any blackening of the bulb, or any greater loss of material from the filament than would have been the case in vacuum at the same temperature. This result was very striking, as the bulb was running so hot that the life of a filament in vacuum, in a bulb at the same temperature, would have been very short indeed. Subsequent experiments fully confirmed the first one, and showed that even in the presence of hydrogen at atmospheric pressure, the loss of weight of tungsten was much less than in vacuum. The loss of heat, however, was so great that it would be entirely impracticable to make a lamp with the tungsten filament in hydrogen at high pressure.

Subsequent experiments showed, however, that the heat conductivity of hydrogen at very high temperature was abnormally great—much greater than would be expected from the ratio of its heat conductivity to that of other gases at room temperature. This is due to the fact that at high temperatures hydrogen becomes dissociated into atoms.*

*Langmuir, *Journ. Amer. Chem. Soc.*, 34, 860, (1912).

Experiments were next tried with tungsten filaments in mercury vapor. It was found here that the heat loss by convection is extremely small—in fact, so small that a filament could be run for a period of a minute or so, at least, at a specific consumption of 0.23 watt per candle. Even the first experiments showed that the presence of the mercury vapor very greatly decreased the rate of evaporation.

Experiments were then tried in nitrogen at atmospheric pressure. Nitrogen was found to be entirely inert towards the tungsten, and to conduct so little heat that with a fairly large diameter filament the specific consumption was as low as 0.24 watt per candle, at a temperature close to the melting point of tungsten. The rate of evaporation was found to be much less than in vacuum.

For tungsten filaments in these three gases, hydrogen, nitrogen and mercury vapor, the "washing" theory certainly did not apply. On the contrary, instead of increasing, they actually very materially reduced the rate of evaporation.

The next point to be determined was whether the decrease in evaporation was sufficient to offset the heat lost by convection. Because of the presence of the gas, the temperature of the filament was run considerably higher than in vacuum, in order to obtain the same efficiency. Whether or not the rate of evaporation in gas at this *higher temperature* would be less than the rate of evaporation in vacuum at the same efficiency, is a point to be determined only by experiment.

A careful study was therefore undertaken of the laws of heat convection from filaments at high temperature in various gases, since the knowledge on this subject was extremely meager. Experiments were made with platinum wires in air, with platinum wires in carbon dioxide and in hydrogen, and with tungsten wires in hydrogen, nitrogen, mercury vapor and argon.

It was shown* that the heat loss varies with the temperature, according to a simple function of the heat conductivity of the gas; and that it varies with the diameter of the wire according to a rather complicated equation, which, however, accurately expresses the relation between diameter and heat loss. This work indicated that the heat lost by convection increases at high temperatures rather slowly with increase in temperature in the case of nitrogen and mercury vapors, but very rapidly in the case of hydrogen. Further, it was shown that the heat loss from

*Langmuir, TRANS. A. I. E. E. XXXI, p. 1011, (1912)
Langmuir, *Phys. Review*, 34, 401, (1912)

very small wires, say 0.001 in. in diameter, is not very greatly different than that from wires several times this diameter. In other words, it was found that it is much more nearly correct to say that the heat loss by convection from small wires is independent of the diameter, than to say that it varies proportionally with the diameter.

According to the formulas developed in the course of this work, the heat loss from wires of any size in any of the ordinary gases at any temperature could be calculated.* In this way,

Specific Consumption (in Watts per Candle) of Tungsten Filaments in Nitrogen at Atmospheric Pressure, as Compared to that in Vacuum

Absolute temp.	In vacuum	Diameter in inches						
		0.001	0.002	0.005	0.010	0.020	0.050	0.100
2400°	1.00	4.80	3.13	2.02	1.59	1.35	1.18	1.11
2600	0.63	2.53	1.71	1.14	0.93	0.81	0.72	0.69
2800	0.45	1.54	1.07	0.74	0.62	0.53	0.50	0.49
3000	0.33	1.00	0.71	0.50	0.43	0.39	0.36	0.35
3200	0.26	0.70	0.51	0.37	0.33	0.30	0.28	0.27
3400	0.21	0.52	0.39	0.30	0.26	0.24	0.23	0.22
3540	0.20	0.45	0.34	0.27	0.24	0.22	0.21	0.21

Specific Consumption (in Watts per Candle) of Tungsten Filaments in Mercury Vapor at Atmospheric Pressure, Compared to that in Vacuum

Absolute temp.	In vacuum	Diameter in inches						
		0.001	0.002	0.005	0.010	0.020	0.050	0.100
2400	1.00	2.30	1.77	1.38	1.24	1.16	1.10	1.07
2600	0.63	1.30	1.03	0.84	0.78	0.72	0.67	0.67
2800	0.45	0.84	0.68	0.57	0.53	0.50	0.48	0.47
3000	0.33	0.57	0.47	0.40	0.36	0.36	0.35	0.34
3200	0.26	0.41	0.35	0.30	0.28	0.28	0.27	0.21
3400	0.21	0.32	0.28	0.25	0.23	0.23	0.22	0.22
3540	0.20	0.29	0.25	0.23	0.22	0.21	0.21	0.20

the accompanying table was prepared, which gives the calculated relation between the watts per candle and the temperature for filaments of various diameters of tungsten in nitrogen, and in mercury vapor.

It is readily seen from these tables that the loss of efficiency

*It makes relatively little difference whether the wires are placed vertically or horizontally. The heat lost *by convection* is usually 5 to 10 per cent less when the wire is vertical than when it is horizontal.

(at constant temperature) due to the introduction of a gas at high pressure is very much greater for filaments of small size, than for the larger ones, so that with wires of the sizes ordinarily used in lamps the temperature would have to be raised excessively in order to obtain a specific consumption of even one watt per candle. Thus in nitrogen a filament of 0.001 inch diameter (the size ordinarily used in a 20-watt, 110-volt lamp) would have to run at 3000 deg. to give one watt per candle. At this temperature of filament, the life of the ordinary lamp would be about 20 minutes, or about one fifteen-hundredth as long as that when running normally at one watt per candle in vacuum.

With filaments of larger diameter (0.005 inch and more), the loss of heat by convection is not nearly so serious, so that, if the rate of evaporation of the metal is very largely reduced by the presence of the gas, it should be possible to raise the efficiency considerably without shortening the life.

The advantages of a large diameter filament can be practically obtained by coiling a smaller wire into a tightly wound helix or otherwise concentrating it into a small space.

The further development of this type of lamp will be described in the second part of this paper.

Changing Location of the Deposit. In lamps with a very high vacuum, the atoms of tungsten as they are given off from the filament by evaporation, travel in straight lines until they strike the bulb. As they are electrically uncharged (this has been demonstrated by experiment), the field produced by the filaments has no influence on the location of the deposit. Since the light from the filament also travels in straight lines, according to similar laws, it follows that in a high vacuum the deposit always collects most on those portions of the bulb where the greatest intensity of light passes through the glass.

In an imperfect vacuum, especially in the presence of argon, the tungsten atoms tend to become negatively charged and thus often deposit on the bulb very irregularly.

With pressures of nitrogen less than 50 mm., the brown deposit of nitride is distributed over the bulb in much the same way as the tungsten deposit in ordinary lamps. At higher pressures than this the effects of convection currents become apparent, and an increasingly large part of the evaporated material is carried to the upper part of the bulb. At atmospheric pressure this effect is very striking, the bulb on a level with the filament usually remaining perfectly clear, while a dark deposit

gradually forms on the portion of the bulb (or supports) directly above the filament.

This fact is of great importance in connection with lamps containing high pressures of gas. Not only does the gas decrease the rate of evaporation, but it may be made, by proper design, to prevent entirely the blackening of those parts of the bulb that transmit the light.

Summary

1. The efficiency at which the larger sizes of tungsten lamps may be profitably run, is limited principally by the blackening of .the bulb.

2. It has usually been considered that the blackening of ordinary lamps was due very largely, if not entirely, to the presence of residual gases. The evidence which has led to this belief is discussed.

3. The sources of gases within the lamp are studied, and the principal gases are found to be water vapor, carbon dioxide, carbon monoxide, hydrogen, nitrogen, and vapors of hydrocarbons.

4. The specific effects produced by these and other gases are determined. It is found that water vapor, which has long been known to be harmful, is the only one that produces perceptible blackening of the bulbs.

5. The blackening by water vapor is due to a cyclic process in which the water oxidizes the tungsten and is itself reduced to *atomic* hydrogen. The tungsten oxide volatilizes and deposits on the bulb, where it is reduced by the atomic hydrogen to metallic tungsten and water vapor is again formed.

6. Attempts to materially improve the life of lamps by the more complete removal of water vapor result in failure. It is therefore concluded that, although water vapor is usually the cause of the short life of poorly exhausted lamps, yet it is not the cause of blackening in well exhausted lamps.

7. The real cause of blackening in well made lamps is proved to be evaporation of the filament, due to its temperature alone.

8. It therefore follows that to improve the efficiency of tungsten lamps, either the rate of evaporation of the filament must be reduced or the evaporated tungsten must be prevented from blackening the bulb.

9. The following methods of improving the tungsten lamp and thus increasing its efficiency, are then discussed in detail:

Introduction of gases, such as nitrogen, mercury vapor, or argon, into the bulb at atmospheric pressure.

Changing the location of the deposit by means of convection currents in gases, so that the bulb opposite the filament does not darken.

10. These methods have met with marked success. The second part of this paper will deal with a particular type of lamp; *i.e.*, a tungsten lamp containing nitrogen at about atmospheric pressure.

A paper presented at the 286*th Meeting of the American Institute of Electrical Engineers, New York, October* 10, 1913.

TUNGSTEN LAMPS OF HIGH EFFICIENCY—II

NITROGEN-FILLED LAMPS

BY IRVING LANGMUIR AND J. A. ORANGE

The first part of this paper outlined principles upon which radical improvements in the efficiency of tungsten lamps may be based.

It was shown that the desired improvement can be obtained by preventing evaporation of the filament or by preventing blackening of the bulb. By the introduction of considerable pressures of such gases as nitrogen, mercury vapor or argon into the lamp the blackening can be practically avoided and the evaporation of the filament reduced very considerably.

By making use of these principles we have been able to construct practical tungsten lamps which, starting at a specific consumption of about 0.40 watt per candle, have run over two thousand hours, the average specific consumption during life being less than 0.5 watt per candle. It should be pointed out at the outset, however, that such a degree of improvement as this has been reached only in lamps taking large currents.

In this second part of the paper we will describe the methods by which these results have been attained.

The early experiments with lamps containing nitrogen at atmospheric pressure were made with ordinary single loop filaments of 0.005 and 0.010 inch diameter placed in long heater lamp bulbs. These lamps were set up on life test at such a voltage that the temperature of the filament was 2850 deg. K.

In order to compare these with ordinary lamps, similar lamps with evacuated bulbs were set up on life test with the filaments at the same temperature.

The nitrogen-filled lamps with the filaments 0.005 inch dia-

meter had a specific consumption of 0.65 watt per candle and had a life of about 90 hours, whereas those with the larger filaments (0.010 inch diameter) had a specific consumption of 0.56 watt per candle and a life of about 300 hours. The bulbs opposite the filaments remained clear, although a slight brown deposit of tungsten nitride collected in the upper part of the bulbs. The candle power of these lamps remained above 80 per cent during their entire life, failure being due in every case to breakage of the filament after this had decreased considerably in diameter.

The vacuum lamps, on the other hand, had a specific consumption of 0.41 watt per candle, but the bulbs blackened rapidly, the candle power falling to 80 per cent in about 40 minutes. Since the filaments of the vacuum lamps burnt out after 2 to 5 hours whereas those of the nitrogen lamps lasted 50 to 100 times as long, it is evident that the rate of evaporation of the tungsten is materially reduced by the presence of the nitrogen.

These results indicated clearly the desirability of using a filament of large diameter. The larger filaments gave not only a better efficiency at any definite temperature, but also a much longer life. Thus doubling the diameter decreased the specific consumption from 0.65 to 0.56 and increased the life from 90 to 300 hours. The improvement in the efficiency, as was pointed out in the first part of this paper, is due to the relatively greater heat loss by convection from small wires. The life of the filament is determined largely by the loss of tungsten from the filament by evaporation and has been found to be dependent on the *relative* decrease in diameter caused by this evaporation. If the rate of evaporation per unit area from large and small wires were the same, the lives of various filaments run at a given temperature would be roughly proportional to their diameters. However, as the evaporation of tungsten in nitrogen is largely a diffusion process, it probably obeys laws similar to those of conduction or convection of heat from a wire; that is, for wires of small diameter, the actual amount of tungsten evaporated would be nearly independent of the size of the wire. The rate of evaporation *per unit area* would thus be approximately inversely proportional to the diameter. The relative lives of very small wires in nitrogen are therefore nearly proportional to the squares of their diameters.

Design of Filament

These results were decidedly encouraging, for both the efficiency and the life of the lamps can be improved by increasing the diameter of the filament.

It is, however, not desirable to use filaments of very large diameter if similar results can be obtained with smaller ones. The current taken by a filament increases approximately with the three-halves power of the diameter. Thus, for wires of the sizes used in the preceding experiments, the currents needed to maintain a temperature of 2850 deg. were approximately:

Diameter		Current
inches	mm.	amps.
0.005	0.127	3.0
0.010	0.254	8.5
0.020	0.508	24.0

Unless very low voltages are used, the power consumed with the larger wires is so great that only very high candle power lamps can be made.

Therefore it was of vital importance to increase the effective diameter of the filament without decreasing its resistance, and various methods of doing this were tried.

This result may, for example, be obtained by using a tubular filament. The method which has thus far proved most satisfactory, however, is to wind the filament into the form of a tightly coiled helix.

The use of a helically wound filament presents several very interesting features. The life of ordinary single loop filaments is limited by the irregularities in diameter which develop after a considerable amount of tungsten has evaporated. These irregularities, after they first appear, tend to magnify themselves very rapidly, on account of the tendency for the current to overheat any spot which becomes thinner than the rest of the filament. The overheating increases the rate of evaporation and rapidly causes failure.

In the gas-filled lamps, however, when helically wound filaments are employed, a new factor is introduced which entirely counteracts this tendency to overheat in spots. In designing the filaments of these lamps, it is evidently desirable to wind the filament on as large a mandrel as possible, in order to obtain the advantage of the large diameter. Since tungsten is a relatively soft material at the operating temperature of these lamps, too large a mandrel should not be used, as otherwise the weight of the filament pulls out the helix very materially in a few

hours, and the heat lost by convection may thus become greater than if a helix of smaller diameter had been used. In actual practise the filament is designed so that the amount of sagging during life will be perceptible, but not enough to cause too great a change in the characteristics of the lamp.

If, during the life of the lamp, any part of the filament should, for any reason, evaporate more rapidly than the rest, so that the filament becomes somewhat thinner, this portion will have less mechanical strength than the rest and will therefore sag more rapidly. The helix will therefore open out wherever the filament becomes thin or becomes overheated. This will cause increased heat loss both by convection and radiation, and thus prevent local overheating or spotting.

The use of helically wound filaments increases the life of the lamp many times beyond the life that would be obtained with a straight filament running, at the same efficiency. This is especially true of the smaller sizes of wire.

Besides the helically wound filament, various other forms have been tried, and, for special purposes, many of these have decided advantages.

Design of Bulbs and Location of Filaments

In the ordinary evacuated lamp, the choice of a suitable bulb is a comparatively simple matter. It must be of convenient size and shape, and provide sufficient room for the proper mounting of the filament. Furthermore, it must have as large an inside surface as possible, so that the density of the deposit of evaporated tungsten will be small. It is also desirable to have the bulb at a sufficient distance from the filament and so related to the power input into the lamp that the bulb does not become overheated. This latter is not only desirable from the point of view of safety (in case of lamps for domestic service), but because it is difficult to remove water vapor so thoroughly from the bulbs that the life of the lamps will not be greatly shortened by an overheating of the glass.

In the nitrogen-filled lamps, however, several other factors must be considered, especially in the lamps of high candle power.

In ordinary lamps about 20 per cent of the energy radiated from the filament is intercepted by the glass and causes heating of the bulb. In the nitrogen lamp, beside this radiated heat, there is an additional amount of heat carried to the bulb by convection—an amount varying with the type of lamp and

ranging from 6 to 40 per cent of the total input. The convection currents carrying this relatively large amount of heat travel vertically upwards from the filament and strike a relatively small area of the bulb, which thus tends to become greatly overheated. Unless special precautions are taken, this overheating will cause the liberation of enough water vapor to cause attack of the filament and consequent blackening of the bulb. It is thus highly desirable, in ordinary cases, if small bulbs are to be used, that the filament should be placed in the lower part of the bulb. This has the further advantage that it allows sufficient surface of glass in the upper part for the deposition of the tungsten nitride.

For a similar reason it is generally desirable, although not necessary, to make the bulbs with their height considerably greater than their horizontal diameter.

By special design of the bulb, satisfactory lamps have been made with bulbs of only one-half to one-third as large a volume as that of evacuated lamps of the same wattage. This means that for bulbs of the same volume the nitrogen lamps give roughly from five to ten times the candle power of evacuated lamps. The bulbs of such lamps naturally run much hotter than those of ordinary lamps. The upper parts of the bulbs are often at 100 to 200 deg. cent. or more, while the lower parts are sometimes much cooler than this, although closer to the filament.

Several special varieties of heat-resistant glass have been used for the bulbs, which can thus be made smaller, while it becomes easier to get rid of water vapor. Transparent quartz bulbs have been tried, but do not seem to have sufficient advantage over some of the special glasses to offset their present high cost.

Lead-in Wires and Supports

For some of the larger size lamps which take heavy currents (20-30 amperes) it has been necessary to devise special types of lead-in wires. The ordinary platinum leads have been discarded entirely, even in the smaller sizes. Several types of heavy current leads have been successfully used. Most depend on the use of special alloys which have the same coefficient of expansion as the glass. Bulbs of special glasses into which tungsten or molybdenum wire can be sealed directly, have also been used.

In many of the larger lamps the lead-in wires pass through the lower end of the lamp. In this case they can be made

short. In others, however, the leads are brought in from the top. This requires more care in the construction of the seal if it is exposed to the heat from the convection currents. Screens are sometimes used to protect the seal or other glass parts from direct contact with the convection currents, and to reduce convection.

Various Types of Nitrogen-Filled Lamps

We have seen that at constant temperature, both the efficiency and the life improve as the diameter of the wire is increased. With very large wires (0.020 to 0.040 inch diameter) which take 20-60 amperes, the specific consumption may be as low as 0.40 watt per candle and probably even less, and yet give a life over a thousand hours. It will probably be worth while, in some cases, to use nitrogen in low-current lamps, even if an efficiency no better than that of vacuum lamps is obtained, in order to gain certain other advantages of the nitrogen-filled lamps, such as better color of the light, higher intrinsic brilliancy, etc.

The principal limitation of the new type is therefore that of current. There is no practical upper limit to the current, provided the voltage is not lowered to keep constant power consumption.* With increasing current, larger and larger filaments are used and the specific consumption may be lowered towards the limit of 0.20 watt per candle, which is fixed by the melting-point of tungsten. Unless special expedients are employed, the cooling effect of the leads lowers the efficiency of the lamps by an amount that is inversely proportional to the voltage and nearly independent of the size of the wire or the current strength.

With voltages of 20 volts or more, this effect is not serious, but for voltages as low or lower than 10 volts, it may become very important.

For the particular type of nitrogen-filled lamp which has at present been furthest developed, it may be said that a life of over 1500 hours is obtained at a specific consumption less than 0.50 watt per candle only in large units taking over ten amperes. Lamps running at 0.6 to 0.7 watt per candle have been made in units taking at least 5 amperes.

No serious difficulty has been met in making high-voltage

*As an example, a lamp taking 60 amperes and giving 6600 candle power at 0.40 watt per candle has been successfully run.

lamps. In nitrogen at atmospheric pressure with properly constructed lamps there is no tendency toward arcing, even at 250 volts. Many lamps taking 6 or 7 amperes at 110 volts have been made up and run at 0.6 to 0.7 watt per candle, with a life of over 1000 hours.

A number of special types of nitrogen-filled lamps have been made and tested. Among these the most interesting, for the present, are perhaps the following:

1. *Large Units of Very High Efficiency* (0.4 *to* 0.5 *watt per candle with a life of* 1500 *hours or more*). These take currents of 20 to 30 amperes and (except in units over 4000 candle power) are therefore best run from a-c. circuits by means of small transformers or auto-transformers giving a voltage depending on the size of unit desired. Thus, with 30 volts and 25 amperes, the power would be 750 watts and this, in a lamp at 0.45 watt per candle, would give 1670 candle power. Higher or lower candle power may be obtained by using other voltages. Typical lamps of this kind are shown in Figs. 1 and 2.

2. *Small Units of Low Voltage.* These take currents of ten amperes or less and voltages as low as four or five volts. The specific consumption with 1000-hour life ranges from 0.6 to 1.0, or even 1.25 watt per candle, according to the current used.

These lamps are adapted for series street lighting on 6.6-ampere circuits (at 0.6 to 0.7 watt per candle), for stereopticon lamps, automobile headlights and in general wherever a source of high intrinsic brilliancy, steadiness and white color is needed.

3. *Lamps to Run on Standard Lighting Circuits* (110 *volts*). Large units of this type (several thousand candle power) have a specific consumption of 0.5 watt per candle or less. With smaller units the efficiency is ordinarily not so high.

A lamp of this type is illustrated in Fig. 3. The leads may be brought in from the top, in which case they are preferably made longer so that the filament remains in the lower part of the bulb.

Special Advantages of the Nitrogen-Filled Lamps

Besides its high efficiency, the features of the new lamps which may, at least for certain purposes, prove of advantage, are:

1. *Color of the Light.* The temperature of the filament being 400 to 600 deg. higher than that of ordinary lamps, causes the light to be of a very much whiter color, so that it comes closer to daylight than any other form of artificial illuminant except the d-c. arc and the special Moore tube containing carbon dioxide.

The color is almost exactly like that which can be had for a few minutes by running an ordinary tungsten lamp at double its rated voltage.

Work is at present under way to develop special color screens

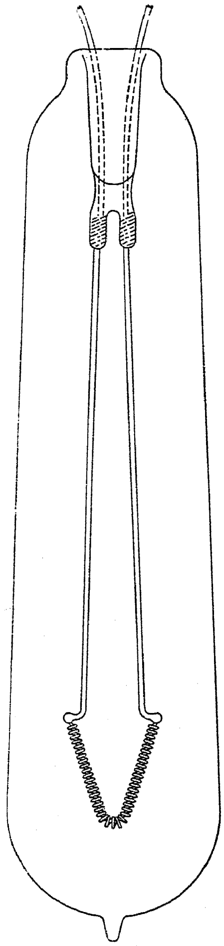

FIG. 1—HIGH EFFICIENCY NITROGEN-FILLED LAMP FOR LOW-VOLTAGE CIRCUIT

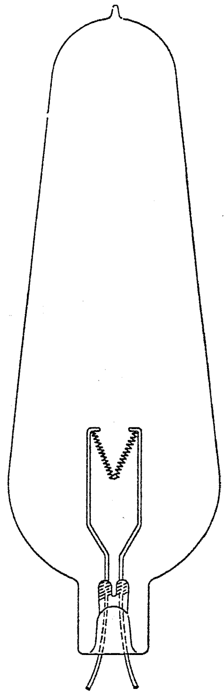

FIG. 2—HIGH EFFICIENCY NITROGEN-FILLED LAMP FOR LOW-VOLTAGE CIRCUIT

which, when used with this light, will give a true daylight color (corresponding to the radiation from a black body at 5000 deg. cent.). From measurements with the spectrophotometer, it can be calculated that the screens which will accomplish this

purpose will absorb from 65 to 75 per cent of the light, so that the net specific consumption will be about 1.5 to 2.0 watts per candle for a pure daylight color. At present, to accomplish this purpose with ordinary tungsten lamps, screens must be used which absorb so much light that the total specific consumption is between 10 and 12 watts per candle. .

2. *High Intrinsic Brilliancy of the Filament.* At the operating temperature of the nitrogen-filled lamps the intrinsic brilliancy

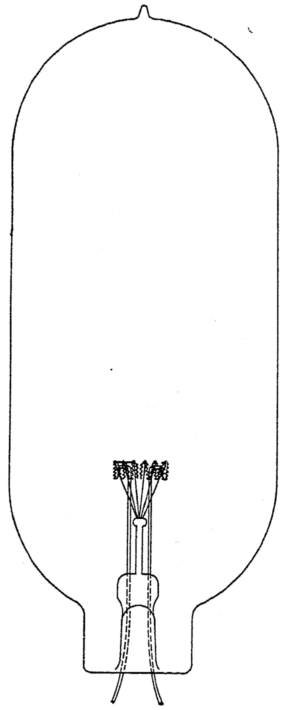

FIG. 3—NITROGEN-FILLED LAMP FOR 110-VOLT CIRCUIT

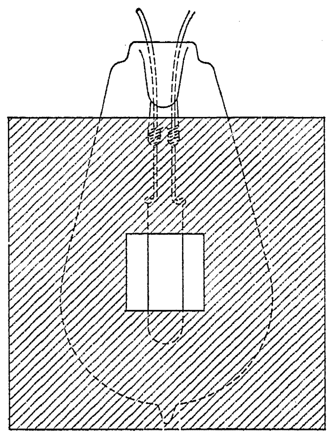

FIG. 4—LAMP AND SCREEN USED FOR CALIBRATION OF BLUE GLASS

of the filament is about 1200 candle power per sq. cm. In ordinary tungsten lamps, on the other hand, running at about 1.25 watts per candle, the filaments have a brilliancy of only about 150 candle power per sq. cm. The brilliancy of the filament of the nitrogen lamp is thus about eight times that of the ordinary lamp.

This feature, combined with the high degree of concentration

preferably used, renders these lamps particularly useful for projection work, such as for headlights or for stereopticons.

3. *Constancy of Characteristics During Life.* It is often possible so to design these lamps that their ampere-,volt-, candle power characteristics remain practically fixed during the greater part of their life. In any case, however, since there is no deposit on the bulb to cut off the light, the candle power practically never falls below 75 per cent (this decrease sometimes being due to sagging). The lamp usually fails by the breakage of the filament with the candle power well above 80 per cent of its original value.

APPENDIX I

Light Distribution of Nitrogen-Filled Lamps. In the preceding paper, wherever the specific consumption of lamps has been given, it is expressed in watts per horizontal (international) candles measured in the direction perpendicular to the plane of the filament if this is in the form of a single loop.

Careful measurements have shown that with helically wound filaments the distribution of light in a horizontal plane is almost perfectly uniform, therefore the specific consumption that has been given may be considered to represent also watts per mean horizontal candle.

The spherical candle power of many of the lamps has been measured. The ratio of mean spherical to maximum horizontal (practically mean horizontal also) candle power has been found to average about 84 per cent for the lamps made with single loops of helically wound wire.

APPENDIX II

Method of Photometry for Nitrogen-Filled Lamps. The usual practise in dealing with incandescent lamps is to determine volts, amperes and candle power either at a predetermined value of one of these quantities or else at a predetermined efficiency by the "cut and try" method. In the case of a lamp which presents so many variables as does the nitrogen-filled lamp, however, it is more systematic to regard temperature as the fundamental variable.

The method that has been adopted for these lamps is not essentially novel, although it does not appear to be as well known as it deserves to be.

First: The temperature has been defined by the equation

$$T = \frac{11{,}230}{7.029 - \log H}$$

where T is the absolute temperature and H is the intrinsic brilliancy of the filament in international candle power per sq. cm. (projected area).*

Second: A most useful criterion in practise for equality of temperature of tungsten filament is that of color-match.

A little practise with the Lummer-Brodhun photometer enables one to judge equality within about 5 deg. if the illumination is good. The most convenient way of setting up temperature standards is to select a number of well-seasoned lamps of high-voltage type in which the anchors are tightly pinched onto the filaments so as to prevent variable cooling effects at the contact. It is best to standardize these, not on a basis of candle power and filament dimensions, but by the aid of a special lamp and diaphragm as shown in Fig. 4. This lamp is arranged at one end of the photometer with the diaphragm in front of and at a known short distance from it. The filament is preferably stout (say 10-mil or 0.025-cm.) so as to admit of good micrometer measurements.

The diaphragm enables one to disregard the end portions of the filament and select a known length of the part which is at uniform temperature. Of course a simple geometrical correction based on the position of the screen is necessary.

It is thus possible to set up the special lamp at any temperature desired by getting the appropriate candle power per sq. cm. from the filament. The standard lamps are brought to color-match with this arrangement and in this way a set of lamps with known relation between voltage and effective temperature is obtained. The life of the ordinary standard lamps would be very short indeed if they were run at the same temperature as nitrogen-filled lamps. For this work, therefore, the standards cannot be used directly as color-standards. For this reason a most important accessory is introduced in the form of a set of special blue glasses. It is not easy to get a blue screen which will perfectly facilitate color-match of tungsten filaments at dif-

*(The derivation of this formula together with a description of other methods of obtaining the temperature of filaments will soon be published, probably in the *Physical Review*.)

ferent temperatures, but a special blue glass has finally been obtained which answers exceedingly well.

Four distinct screens of different intensity are used, each carefully finished as a uniform plate, and any or all of these may be combined with a tungsten filament run at any temperature and the result will color-match correctly against another tungsten filament at a higher temperature.

It may be shown theoretically and experiment confirms that the following relation holds:

If T is the temperature of a filament which is viewed through screens A, B, C, etc.,

T_1 is the temperature of a filament which matches the above.

Then $\frac{1}{T} - \frac{1}{T_1} = a + b + c$ etc.

where a, b, c etc. are constants for the screens A, B, C, etc. Thus one only needs to maintain one standard temperature by means of standard lamps and that temperature can be so low that great permanence is insured.

The constants for the four glasses once determined, there are available a number of standard temperatures ranging from 2250 deg. to 3600 deg. K.

By the use of these screens it is an easy matter to set a lamp up at a voltage such that the filament has a standard temperature, say 2850 deg. To do this it is simply necessary to adjust the voltage so that the color of the light from the lamp is the same as that which comes from the standard lamp when viewed through one of the special blue screens.

Since the efficiency in vacuum is very simply related to the color of the light, this method of photometry gives a very simple and direct way of knowing the exact effect which the nitrogen has on the efficiency of the lamp.

DISCUSSION ON "TUNGSTEN LAMPS OF HIGH EFFICIENCY—I AND II" (LANGMUIR AND ORANGE), NEW YORK, N. Y., OCTOBER 10, 1913.

John B. Taylor: I would first like to make a few remarks, to give the audience a few moments' time in which their eyes may become accustomed to the great difference in brilliancy between the filaments they have just been looking at and the enlarged projected image, which, perhaps, will have a brilliancy of something in the order of one-millionth part of the brilliancy of the lamps at which you have been looking.

I can testify to the satisfaction that this lamp gives in projection work after using the lamp with a projecting microscope and also for photomicrographic work, particularly color photography. The steadiness of the lamp as compared with an arc lamp, either hand-fed or automatic, leaves the worker absolutely free to give all his attention to the subject or specimen and the photographic plate. A switch turns on the lamp and the light source is always exactly in the same position. Its intensity will always be the same, and repeated exposures will give similar results. The color value is good, as it is almost as white as a carbon arc. In projection work half of the light is thrown backward, but a large portion of this can be conserved by the use of a reflecting mirror, properly placed so that the reflected image practically coincides with the source of light. The projection arrangement I have here will show this. This reflector arrangement is of no value in the case of the carbon arc, as the electrode casts a shadow backwards. As shown in Fig. 1, the reflected image is inverted with respect to the direct image.

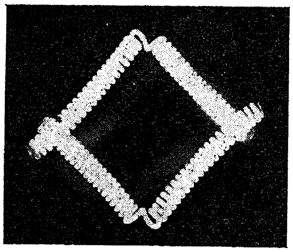

FIG. 1

(Mr. Taylor then threw the projection on the screen.)

I ask Dr. Langmuir if he can tell us anything of the ratio of the resistances of the filament hot and cold in the nitrogen-filled lamps. This may be an important factor when the lamp is switched on if there is a momentary overload of fifteen or twenty times normal.

John W. Howell: Dr. Langmuir has made an analysis of the residual gases in tungsten lamps, and has devised an apparatus for the making of qualitative analyses in determining the five constituents in one cu. mm. of gas. That is a marvelous achievement. During all the years we have been working on incandescent lamps we have been interested in residual gases, we have known they were there, and we had a general idea what they must be, but we never had the initiative to try to measure them in quality and quantity as Dr. Langmuir has done.

The first summary of Dr. Langmuir's, on page 1932, reads* as follows: "The efficiency at which tungsten lamps may be profitably run, is limited principally by the blackening of the bulb." Dr. Langmuir should have drawn that statement more carefully, so that it would refer to large lamps. It is true of large lamps, but it is not true of the small lamp. Forty-watt lamps and all smaller standard lamps blacken so little that they break before the blackening becomes objectionable and their useful life is their total life. These lamps constitute over 75 per cent of all lamps sold. In large lamps the efficiency is limited by the blackening of the bulb. There are two reasons for this. The small lamps have thin filaments. If these filaments waste away by evaporation, and one spot is hotter than the other, the hottest spot will waste fastest, and it will break there. This wasting will break a thin filament in shorter time than a thick filament, consequently the thin filaments break before the evaporation has proceeded far enough to blacken the bulb. We test in the laboratory all 40-watt lamps at 0.9 watts per candle. Their total life at 0.9 watt per candle is about 400 hr., and at the end of that time they are not blackened sufficiently to render them objectionable or make us take them down. Large-diameter lamps will live longer. Another reason why lamps with thick filaments blacken more than those with thin filaments is that thick filaments are used for high candle power lamps and in these lamps, for practical reasons, the bulb area is not nearly so large relative to the candle power or filament surface as in thinner filament lamps, and as the evaporation from a filament is proportional to its surface, these larger lamps with less bulb surface per unit of filament surface would get blacker in a given time. This difference in bulb surface in relation to filament surface is very great and causes large lamps to become useless by blackening before the filaments break.

As to the second paragraph in Dr. Langmuir's summary, I have recognized for some time that there are three different kinds of blackening in a tungsten lamp, and that the ordinary blackening which proceeds very slowly and is uniform throughout the bulb is caused by the evaporation of the filament. I believe that same thing of carbon lamps, and if you will refer to the TRANSACTIONS of this Institute for March, 1894, you will find a paper written by Prof. Anthony on "Incandescent Lamps Containing Heavy Gases." Prof. Anthony concludes with the statement that the blackening of the carbon lamp is caused by the evaporation of the filament, and Prof. Elihu Thomson, and Prof. Robb, of Hartford, and Mr. Doane agreed, in discussing the paper, that the blackening was due to this cause.

In discussing that paper I said that there were two kinds of blackening, one was due to evaporation, I believed, and the other was not. Now, the other kind of blackening, which I thought was not due to evaporation, is always irregular in its deposition on the bulb. In carbon incandescent lamps we fre-

*As first printed, previous to presentation.

quently met an irregular blackening which we call mottling, and mottling always occurs in a lamp which has a defective vacuum. Of course, there are different kinds of defective vacua, but only a few kinds of defective vacua that produce that mottling. There is one condition which always produced a mottled discoloration of the carbon lamp, and that was in the case of lamps which we made at one time, in which we put a little clay in the anchor clamp to hold the filament. These lamps were always discolored irregularly and with mottling. That same mottled discoloration is found in tungsten lamps. This lamp (exhibiting lamp) illustrates a mottled lamp, but the discoloration is not black. It is a lightish discoloration, caused by oxygen, by air. That is a mottled discoloration. I believe that any residual gas in a lamp which attacks the filament will produce a mottled discoloration.

The other kind of blackening in lamps is due to water vapor. We have believed for a good many years that the gas which comes from the glass of the lamp as it is heated was water vapor, but we did not know it. Dr. Langmuir proves it and now we know it. It is impossible, I think, to exhaust out of a lamp with a mercury pump all of the water vapor which comes off the glass when you heat it. The only way in which we can take it out is by the use of phosphoric anhydrid.

Water vapor in a carbon filament lamp does not cause the lamp to blacken as in a tungsten filament lamp. Here are two tungsten lamps (exhibiting lamps) that were made in the spring of 1907. When we made these lamps we exhausted them together in the same way. After they were exhausted and sealed up as finished lamps, I took one lamp and with a gas torch heated the bulb hotter than it had been heated in exhaustion, and then the two lamps were put up on a life test and burned over night, and the result of one night's burning was that the lamp that had been heated to drive the water vapor off the bulb into the lamp was black the next morning and the other one remained perfectly clear. We discovered also that when we heated the bulb during exhaustion the water vapor was sufficiently removed so it did not come out any more afterward.

Away back, about 1890, there was a lamp put on the market called the novak lamp, a carbon lamp with one mm. of bromine in it. The lamp was not commercially successful because the bromine had, as nitrogen has, bad effects and good effects, but in that carbon lamp the bad effects were greater than the good effects, and the result was a disadvantage and the lamp did not live.

At that time I made a lot of experiments on the effects of gases in lamps. I made measurements with four gases, nitrogen, hydrogen, bromine and chlorine. The lamps I used were first exhausted with a very good vacuum, and then increasing amounts of each one of these gases, separately, were admitted to the lamp, and the change made in the specific consumption of the lamp

by the cooling effect of the gas was noted, and these changes were plotted in a curve which showed the effects of any amount of either one of these four gases in the lamp. At first it was impossible to make a lamp which would burn well with any gas in it. It was only when we realized the absolute necessity of dryness in the gas that we succeeded, but when we got these gases absolutely dry, neither one of them had any ill effects on the lamp. I mean as to making it black; but they all cooled the filament and this cooling effect is what we measured.

The effect of water vapor in a carbon lamp is to render the filament sooty and black. This makes it a very excellent radiator of heat, so that it is cooled by radiation to such a degree that the candle power falls away down, and yet the bulb remains clear.

Farley Osgood: The question that interests the operating engineer is, what is the hope of the development of this lamp in small units? As Mr. Howell has said, 75 per cent of the lamps used are in small units.

J. E. Randall: You have had here an exhibition of this new development and a demonstration of the operation of these lamps during a period of a few moments. I presume that I am the last person in this hall to have seen any lamps of this kind operated in the Research Laboratory at Schenectady. I saw some lamps there today and identified them as those that I saw operating under the same conditions a number of weeks ago. They have been operating continuously since the first time I saw them. Therefore, I think we can say that this development is successful. The development will be beneficial because it marks a long step in the energy efficiency of a device that is notoriously inefficient.

If we grade the quality of lamps by the initial efficiency, that is, filament temperature at which they will show a certain performance, the so-called nitrogen lamp will take a very high rank. If we establish as a standard of performance, the initial efficiency at which a lamp will develop 90 per cent of its theoretical candle hours during one thousand hours of burning, candle maintenance and mortality both considered; and if, on this basis, we call the raw carbon filament lamp 100, the various types will rank as follows:

Raw carbon filament lamp	100
Treated carbon filament lamp	119
Gem filament lamp	149
Tantalum filament lamp	206
Tungsten filament lamp	359
I have not complete data for the new lamp but it surely would have a rating of	600

We should not consider these developments as extending the lives of lamps. Their success should rather be gaged by their energy saving. The real advantage of any improvement in the incandescent lamp is utilized by raising efficiency rather than by prolonging life.

The way for the new lamp was to a great extent prepared by the production of ductile tungsten. Methods of shaping the drawn tungsten wire into helical coils have been so developed that they are of signal assistance. Accuracy of control of wire diameter, which, one may say, has almost reached perfection, will doubtless add speed to the commercial development of this latest lamp.

William McClellan: I ask whether Dr. Langmuir in closing will say a word about frequency in connection with the lamps, especially low frequencies, with low-voltage lamps. Is there any difference between that and the ordinary tungsten lamp?

Irving Langmuir: Different frequencies of alternating current?

William McClellan: Yes. The point is that the ordinary carbon lamp at 25 cycles, low wattage, does not flicker so that it can be noticed. When you come to the tungsten lamp it flickers considerably. I am interested in knowing whether the new type of lamp will be different from the tungsten, or practically the same.

John W. Lieb, Jr.: The question naturally arises, what is going to be the effect of this great movement forward in lamp efficiency on central station service, and what is its effect going to be on the general question of improvements of efficiency and life of incandescent lamps? Undoubtedly these new lamps will necessitate a revision of our criteria which have prevailed hitherto as to what should be considered as the useful life of the lamp. Useful life, as we know, has been established in accordance with general agreement that when the lamp has depreciated in candle power to 80 per cent of its initial value the useful life of the lamp has ended; it has reached the "smashing point." Now, with these new developments in the lamp, and the increased efficiencies which have been attained, it will be necessary for us to modify our figure, or at least give it new consideration in the light of the electrical data which these new lamps present. The central stations have long ago passed that period when they could afford to exhibit any fear as to the ultimate result of an improvement in the art, in any direction in which the art might progress. This new development will help to reach that consummation which we have all been hoping for, that the electric light will reach the humblest home and be as easily accessible to the humblest of our citizens as kerosene.

Another question which is raised by these lamps is, what will become of the arc lamp? I think it is no empty prediction that the arc lamp under the impulse which this new development produces, will achieve further advances to put itself in line to continue the contention with its new competitor.

M. G. Lloyd: We are told that the nitrogen is at about one atmosphere pressure. I ask the reason for using that particular value. I should like to know whether it is considered objectionable to have a higher pressure than one atmosphere inside the bulb.

H. M. Fales: Telephone companies are interested in the success of the tungsten lamp for street lighting purposes. The present carbon arc lamps produce variations in the lighting circuit of such frequencies that serious disturbances are often caused inductively in telephone circuits located on the same street. With tungsten lamps this is not the case. The disappearance of inductive disturbances in telephone circuits has already, in a number of cases, been traced to the substitution of tungsten lamps for arc lamps.

Farley Osgood: I might suggest that Dr. Langmuir in closing say a word about the stability of these lamps. Our friend Mr. Lieb has indicated the possibilities of it for arc use, which is very interesting to operating engineers.

Irving Langmuir: The difference in brilliancy, pointed out by Mr. Taylor, between the inner and outer portions of the helix as thrown on the screen, is due, I think, principally to reflected light from the inner sides of the turns. In other words, the conditions in the interior of the helix more nearly approach those in a so-called " black body " furnace. The difference in temperature between the inner and outer part of the wire may be approximated by calculation, and is found to be less than 10 degrees, an amount too small to account for the large difference in brilliancy.

It might at first sight appear that the imprisonment of light by reflection back and forth between the adjacent turns of a helix causes a waste of light energy. In a sense, this is true, but since the heat energy is also imprisoned to nearly the same degree, the power needed to heat the filament is decreased in about the same ratio as the light. The efficiency at any given temperature is therefore not seriously affected by the helical winding. Experiments confirm this.

Mr. Howell's criticism that the failure of small lamps is due principally to breakage and not to blackening is, I feel, quite correct. In writing the paper I had in mind lamps of 40-watt size, or larger. Although under the usual operating conditions the failure of 40-watt lamps running at normal efficiency is, as Mr. Howell points out, rarely due to blackening, yet our experiments have shown clearly that as soon as the specific consumption of such lamps is lowered to about 0.8 watts per candle, the bulbs blacken relatively rapidly and the candle power often falls to 50 per cent of the initial candle power, or lower, before failure occurs.

I did not mean to claim in the paper that we were the first to find that water vapor in lamps is injurious, or to suggest evaporation as a cause of blackening. I know that the presence of water vapor has been considered extremely harmful, in both carbon and in tungsten lamps, from the early days of their manufacture. I have pointed out that evaporation as a cause of blackening was one of the theories often applied to the blackening of lamps.

I feel, however, that evaporation was considered as a *possible explanation*, rather than as the *known cause* of blackening in well made lamps.

It has been my experience that the men in lamp factories always endeavored to explain every particularly good or "freak" lamp by assuming that the vacuum in the lamp had been better than usual, thereby directly inferring that the presence of residual gases limited the life of ordinary lamps.

Many of the German lamp factories have carried on very careful scientific investigations as to the cause of blackening of tungsten lamps, but so far as I know, have not found evaporation to be the cause.

The prevalent theory among these investigators seems to be that the blackening is primarily due to electrical disintegration. This theory has sometimes been discarded in favor of the evaporation theory, because the rate of blackening apparently did not perceptibly depend on the voltage of the lamp, but did rise rapidly with the temperature of the filament, according to a curve resembling a vapor pressure curve. These were Prof. Anthony's main reasons for concluding that evaporation was the cause of blackening. Investigations during the past ten years, however, have shown that the electrical discharge (thermionic current) from a hot wire in vacuum is independent of the voltage and does rise with the temperature, according to just such a curve as that observed for the rate of blackening. Thus both of the main reasons which had led Prof. Anthony to conclude that evaporation was the cause of blackening fall to the ground.

On the other hand, the objections to the electrical theory which have previously seemed most serious, disappear.

The real reason for our conclusion that evaporation and thermionic currents are not related, is based on actual measurements of these thermionic currents, which are being published elsewhere (*Phys. Review*, Dec., 1913).

What Mr. Howell has said about the uniformity of the deposits caused by evaporation is in accord with our experience. The blackening due to water vapor, however, is not always, or even usually, irregularly deposited, although in some cases it may be so to a marked degree. In some cases we have observed that blackening by water vapor is limited to the hottest portions of the bulb. In fact, if heat is applied locally to a part of the bulb, this alone may blacken. Sometimes blackening in presence of gas is influenced by electrical discharges. But it is more usual even in presence of water vapor, to obtain very uniform deposits, which in appearance cannot be distinguished from those due to normal evaporation.

I may have conveyed a false impression in the paragraph on the effect of argon. That paragraph refers only to argon at very low pressures. Argon at high pressures is just as good, if not better than, nitrogen. The results so far indicate that argon will probably be substituted for nitrogen in the lamps as

soon as it becomes readily available. The gas is very hard to make on a small scale, but on a large scale it can be made very cheaply, comparatively speaking.

In regard to the flicker of these lamps when used on alternating current, I may say that this depends entirely on the size of filament used; in other words, on the current taken by the lamp. With lamps taking 6.6 amperes on 25-cycle current, the flicker is just barely noticeable. With lamps taking larger currents, it cannot be detected by the eye.

The pressure of gas used in the lamps is preferably as high as is consistent with safety. In order to avoid all possibility of explosions, we aim to employ such an amount of gas that the pressure will be about atmospheric pressure during the normal operation of the lamp. The gain in efficiency which could be obtained by using higher pressures is entirely negligible.

The stability of the lamps is as good as that of ordinary lamps. Of all the lamps shipped from Schenectady to New York for this meeting, not one was broken.

In conclusion, I should like to say that I consider the real credit for this work is due to Dr. W. R. Whitney, who, by the encouragement he has given and the wonderful spirit of coöperation he has created in the laboratory, has made the result possible.

A paper presented at the 287th Meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1913.

INDUSTRIAL SUBSTATIONS

BY H. P. LIVERSIDGE

The growth of the demand for electrical energy during the last two decades has been one of the very significant indications of the increasing prosperity of the country at large. Remarkable growth is noted in the demand for electrical energy for all uses, but particularly in the demand for energy for industrial purposes. This latter demand has created certain problems which have necessitated the development of new methods by which energy is delivered to consumers.

It is the purpose of this paper, after tracing very briefly the engineering development of this branch of the central station industry, to give some discussion of the salient features of the design and installation of electrical plant equipment in consumers' premises, which we shall designate as "industrial substations." Certain specific installations will be cited and certain conclusions drawn.

The growth of the supply of electrical energy, by central stations to consumers, for industrial purposes, dates back to the commercial introduction of the electric motor. Starting with the early installations of a few horse power each, the development has been such that at the present time industrial consumers are found with individual installations totalling several thousand kilowatts capacity.

In the early days the industrial consumer was supplied like other consumers, from the regular service mains of the central station. The service was either d-c. or a-c. according to the character of the central station mains. Energy was supplied without the necessity of installing transforming or switching

equipment in the consumer's premises, other than the usual service switches controlling the incoming lines.

It was early seen by operating companies that, due to the increased demand, the method by which energy is brought to the consumer and there distributed would have to undergo marked changes, and that it would be necessary to devise means by which the large blocks of energy demanded could be satisfactorily supplied by the central station. The changes necessary to accomplish these results have affected particularly: (a) the size and location of the transforming apparatus, (b) the character of the equipment required to control these increased capacity installations, and (c) the voltage at which the energy is delivered to the consumer.

Coupled to the greater demand of the industrial consumer supplied from high-voltage alternating-current lines was, oftentimes, the need for direct-current service. This added requirement necessitated the installation of rotating apparatus for transformation from alternating current to direct current, besides the static transformer equipment usually provided.

These larger and more complicated installations practically made necessary the location of the transforming apparatus in the consumer's premises. In addition, many of the larger services made advisable the supply of energy at a higher potential than that of the regular distribution circuits of the central station system, particularly so when the distance of transmission was comparatively long.

The installation of high-voltage services supplying static transformers or rotating transforming apparatus, or both, necessitated an electrical equipment comparable to that installed in central station substations. Moreover, the same care is given to the design and construction. This is clearly evidenced in the industrial substations later cited as examples in this paper.

The present discussion will deal more particularly with large industrial substation installations located in comparatively built-up manufacturing districts, and supplied from high-voltage alternating-current lines. At the outset, consideration must be given to the factors that determine the decision on the part of the operating company whether or not to install a substation in consumers' premises.

In general, when the load does not exceed a few hundred kilowatts and the consumer's demand is for alternating current entirely, it is very usual practise to supply the consumer through

an installation of transformers fed directly from the distribution lines of the operating company. In such cases, no substation is necessary in the consumer's premises.

On the other hand, when the amount of energy demanded requires a heavy capacity transforming equipment, or when the requirements of the consumer are such that a combination service of both direct current and alternating current must be supplied, then it becomes necessary to install protective apparatus and switching equipment of a more elaborate nature than in the former case; and the industrial substation is therefore designed.

The problem of electrical design of industrial substations presents usually no great difficulties. The equipment necessary to meet the requirements of each consumer will be found to have been more or less standardized by the operating company, with such modifications in particular instances as are necessary.

The variations between designs are due in general to differences in the capacities of the installations, the equipment installed, the conditions of service, and the voltages at which the substations are supplied.

The problem of *physical* design very often presents many more difficulties, particularly the disposition of the electrical equipment in the space available. The four factors of: (1) space economy, (2) operating requirements, (3) fire hazard and safety to attendants, and (4) cost, govern in most cases the physical layout.

Not infrequently a decided limitation is imposed on the physical arrangement by the very cramped quarters allotted to the substation equipment by the consumer. On the other hand, the erection of new industrial buildings usually allows space sufficient for proper design of the substation. In the matter of the design of industrial buildings, much room exists at the present time for closer co-operation between the consumer and the central station's engineers, to the consumer's own great advantage.

Contrasts are evidenced both in the electrical and physical designs of industrial substations in different localities in this country, but are no more marked than in the designs of generating stations and substations. It is proposed later herein to cite examples of industrial substations in operation in different parts of the country, and to give descriptions of certain ones which are taken as typical.

For purposes of further analysis, the electrical design of an industrial substation briefly may be divided into the following components: (a) the incoming feeders; (b) the arrangement of the busbars if any are installed, and the switching equipment; (c) the transforming equipment; and, finally, (d) the distribution system of the consumer. This latter is very often left to the consumer himself, and usually is given little attention by the central station engineers.

Detailed discussion of the various components which make up the electrical equipment of an industrial substation as noted above, need not be taken up at this point, but rather consideration will be given to them as they are instanced in the following examples of typical installations, at present in operation in this country.

Plant No. 1

Silk Manufacturing Plant Supplied by Two Industrial Substations Located on Premises. Static transformer equipment only is installed, totalling 1720 kw. in the two substations. The load is of very constant nature, and the service is twenty-four hours a day, seven days a week throughout the year. No regular attendant is required, but general maintenance is provided by consumer's electricians.

The description will be limited to the more recent one of the two substations, which is a fireproof building, 10 ft. (3.04 m.) wide by 30 ft. (9.14 m.) long by 10 ft. 6 in. (3.19 m.) high at lowest point, of brick with concrete; one side adjoins a factory building. Ample provision is made for lighting and ventilation by window openings (fire-resisting glass) and by natural-draft ventilators in the roof.

The substation is supplied at 2400 volts, two-phase, 60 cycles, by two feeders, both entering the building underground from overhead lines. Lightning arrester protection is provided by electrolytic lightning arresters connected to the overhead lines and located in enclosures at the base of the terminal poles.

The present transformer equipment consists of two banks of oil-insulated self-cooled power transformers of 400 kw. capacity each, and one bank of lighting transformers of 60 kw. capacity; making a total of 860 kw. capacity in this substation.

The high-tension switchboard consists of four panels, controlling two incoming feeders and two transformer banks. Connections are as shown in Fig. 1 under " Transformer House No. 2." Automatic hand-operated oilbreak switches are connected in each 2400-volt circuit as shown in the diagram.

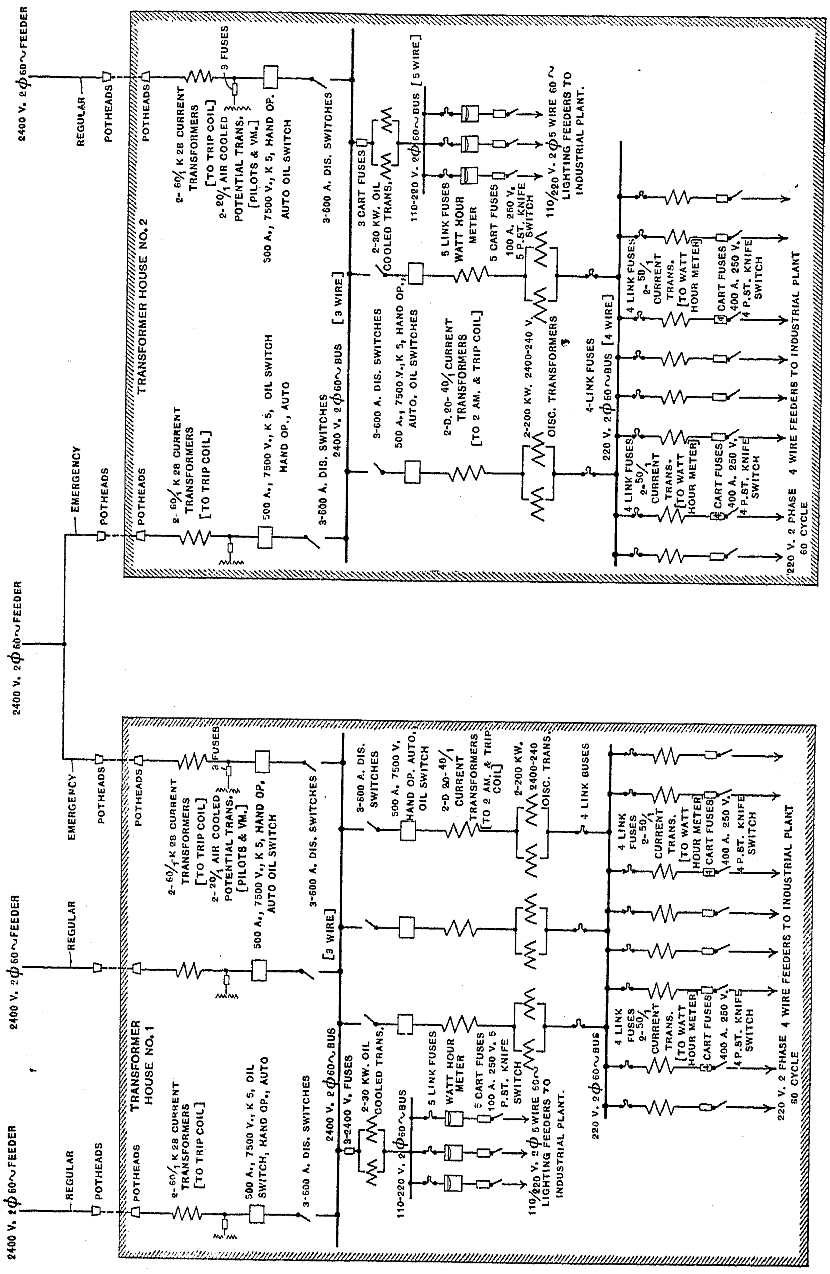

Fig. 1—Electrical Connections of Plant No. 1

All metering is done on the low-tension side of the step-down transformers and the watt-hour meters are connected in the individual industrial feeders. The power feeders are 240-volt two-phase, four-wire, and the lighting feeders 120/240-volt, two-phase, five-wire. All high-voltage wiring in the plant is placed out of reach of attendants and all high-voltage disconnecting switches, busbars, and instrument transformers are protected by asbestos lumber barriers. All power secondary fuses are protected by asbestos shields, and all lighting secondary fuses are enclosed in iron boxes.

The accompanying illustration (Fig. 2) gives a general view of the electrical equipment.

Plant No. 2

Grain Elevator. Substation Located in Specially Designed Two-floor Brick and Concrete Building. This substation is supplied by 13,200-volt three-phase 60-cycle overhead feeder from substation of central station company.

The present transforming equipment consists of three 200-kw. oil-insulated self-cooled single-phase transformers stepping down to 440 volts three-phase three-wire. The ultimate total transformer capacity is 1200 kw. in two banks. Electrical connections are as shown in Fig. 3.

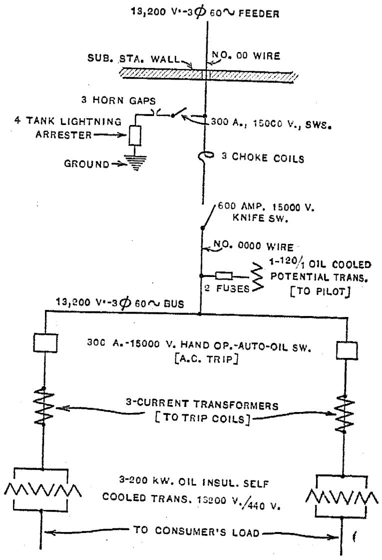

FIG. 3—ELECTRICAL CONNECTIONS OF PLANT NO. 2

Electrolytic lightning arrester equipment with choke coils is installed on incoming feeder at the point of entrance to the substation building. This feeder is taken directly to the two automatic oil switches controlling the two banks of step-down transformers.

All metering is done by watt-hour meters on the low-tension sides of the transformers; the three-wattmeter method of three-phase energy measurement is employed. All oil switches are hand-operated, and the electrical design is essentially one of simplicity.

Provision is made for the safety of the operator by the erection

FIG. 2.—PLANT NO. 1 [LIVERSIDGE]

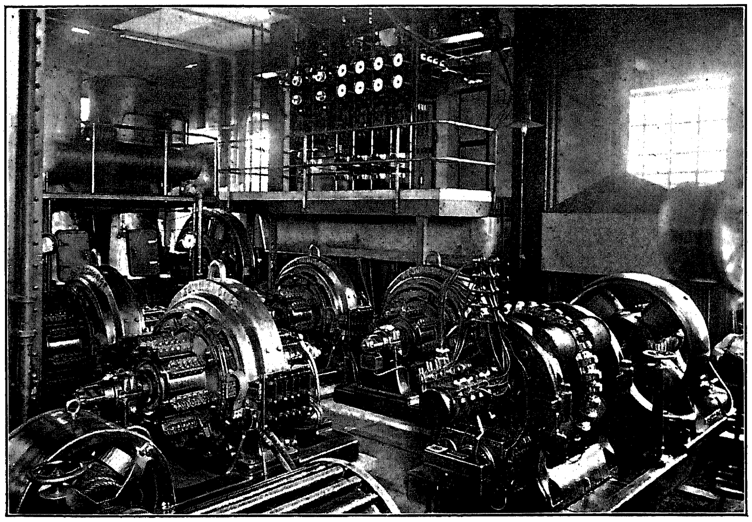

FIG. 4.—PLANT NO. 3 [LIVERSIDGE]

of asbestos lumber barriers, etc., enclosing all accessible high-voltage conductors and parts.

The character of the load is irregular.

Plant No. 3

Ship and Engine Building Plant. Synchronous Converter Substation Located in Consumer's Power House. The substation equipment consists of four 300-kw., 60-cycle synchronous converters, having a total capacity of 1200 kw. and supplying direct-current energy to consumer at 250 volts, two-wire. The substation is arranged for parallel operation, if desired, with two engine-driven direct-current generators of the consumer. The substation is supplied by two 6000-volt, two-phase, 60-cycle

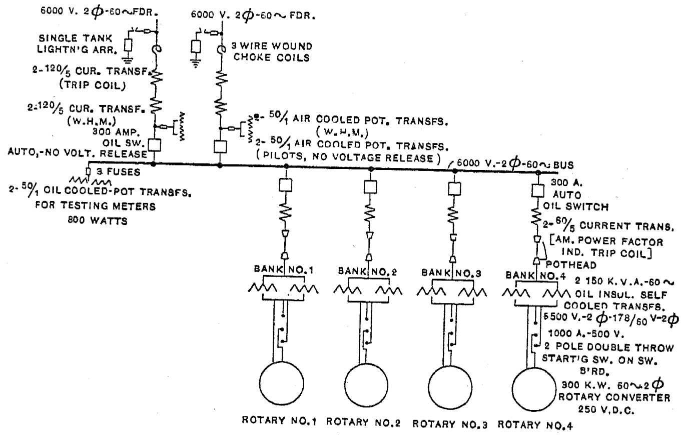

FIG. 5—ELECTRICAL CONNECTIONS OF PLANT NO. 3

feeders brought overhead into the building and connected to a single set of busbars.

Electrolytic lightning arresters and choke coils are installed on each feeder, and automatic oilbreak switches are provided for each feeder and each synchronous converter circuit. The feeder oil switches have a " no-voltage release " feature in addition to the usual overload trip.

All energy is metered by watt-hour meters placed on the two incoming feeders. All high-tension switching equipment and the alternating-current switchboard, busbars and lightning arresters are located on a gallery along one side of the building. The oil-insulated self-cooled transformers for the synchronous converters are located underneath the gallery.

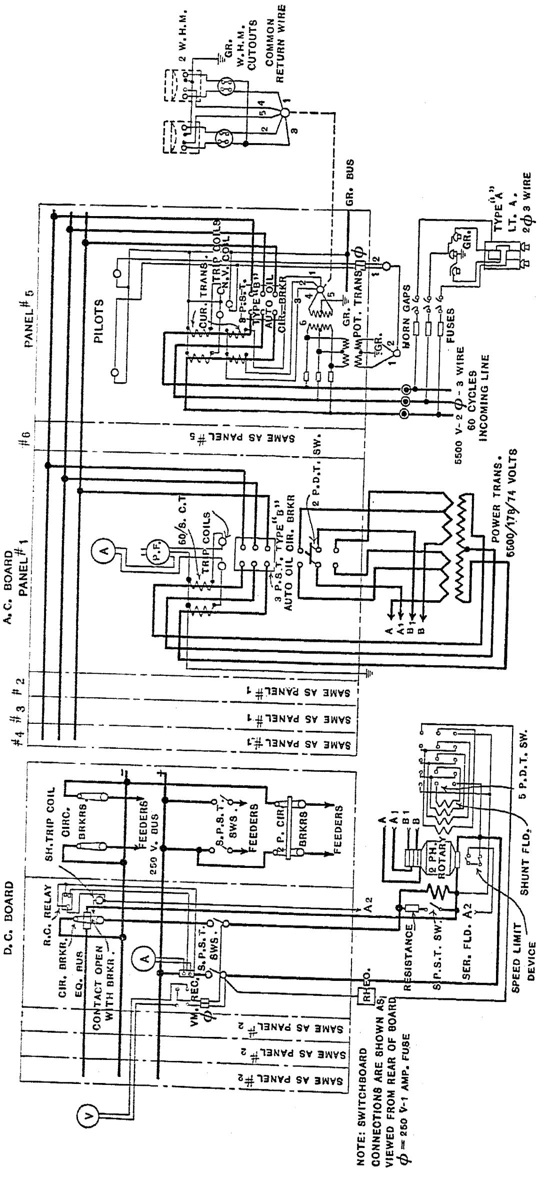

Fig. 6—Detail of Electrical Connections, Plant No. 3

A general view of the plant is given in Fig. 4 and single-line diagram of connections in Fig. 5. Detail connections for the electrical equipment are shown in Fig. 6. Interest attaches to the sheet metal hoods placed over the transformer banks and used for purposes of fire protection and ventilation.

The conditions of service are twenty-four hours, six days a week. Attendance is by the regular operating force employed by the consumer.

Plant No. 4

Static Transformer Substation (Fig. 7) Supplying Amusement Park on Outskirts of Metropolitan District. The equipment is located in a small brick substation building on the park grounds, and consists of 400 kw. transformer capacity at present time, with provision for doubling this capacity when required. Transformation is from 6000 volts, two-phase, 60-cycles, to 2400 volts, two-phase, 60-cycles. Oil-insulated, self-cooled transformers are used. Energy is metered on the low-tension side of the transformers. All oil switches on the high-tension side are non-automatic, for the reason that there is no regular attendant and further that the feeder which supplies the substation is brought directly from a central station substation where the feeder switches are automatic. Electrolytic lightning arrester equipment is installed at both ends of the feeder.

The character of the load is a summer park load of motors and lighting.

Plant No. 5

Synchronous Converter Substation in Car Manufacturing Plant. This is supplied at 13,200 volts, three-phase, 60-cycles, by two underground feeders from a central station substation.

The initial equipment consists of two 300-kw., six-phase, 250-volt, direct-current compound wound synchronous converters with necessary banks of single-phase oil-insulated self-cooled "step-down" transformers. The ultimate converter capacity is 1600 kw. in four units. A single set of high-tension busbars is provided, and the entire high-tension switching equipment is electrically remote-controlled. Also, a high-voltage service is taken off the busbars to additional transformers for fire pump motor. Watt-hour meters are connected on the 13,200-volt incoming feeders.

A specially designed two-story substation building houses all the apparatus. The building is entirely inside the walls of the

industrial plant, but is separated from it by suitable fire-proof walls. The static transformers and high-voltage equipment are located on the second floor; the synchronous converters, the direct-current switchboard and the remote control board for the high-voltage oil-break switches are placed on the first floor.

The plant operates in parallel with an existing direct-current steam-driven plant.

An interesting point in connection with the consumer's distribution system is the provision for electrical remote control of the 250-volt direct-current supply switches which are located in various parts of the manufacturing plant. These separate services are tapped to heavy capacity feeders, arranged in a ring system, and the service switches are controlled from the industrial substation.

The character of service at this plant is ten hours per day, six days per week, and the attendance is supplied by the consumer.

Fig. 8 shows elevation of the substation and illustrates the general arrangement of the electrical equipment.

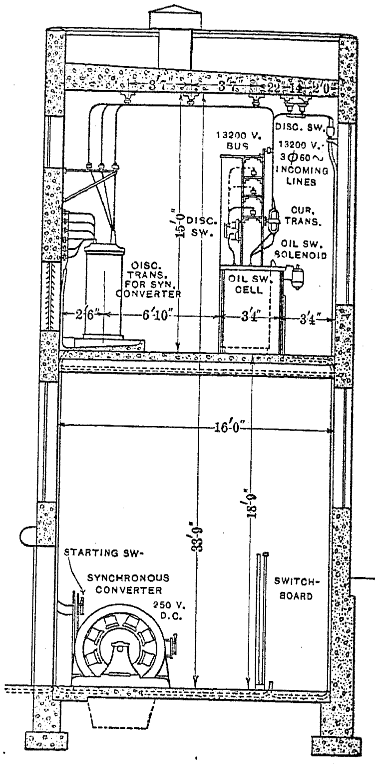

FIG. 8—SECTIONAL VIEW OF PLANT NO. 5

Plant No. 6

Static Transformer Industrial Substation of Paper Manufacturing Plant. Current is supplied at 6600 volts three-phase by two incoming feeders, one of them brought directly from generating station and the other from a substation.

The transforming equipment consists of six 150-kw., 6600/440-volt, single-phase power transformers, arranged in two banks of three transformers each, giving a total connected capacity of 900 kw.

The feeders are taken through automatic oil-break switches to a single set of busbars connected to a line containing current

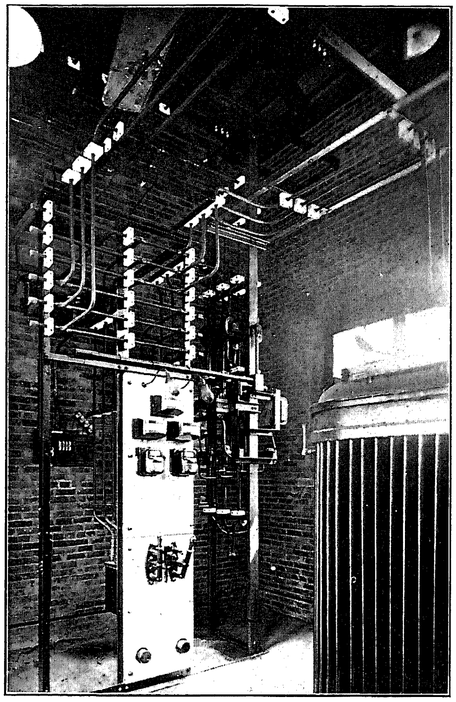

FIG. 7.—PLANT No. 4 [LIVERSIDGE]

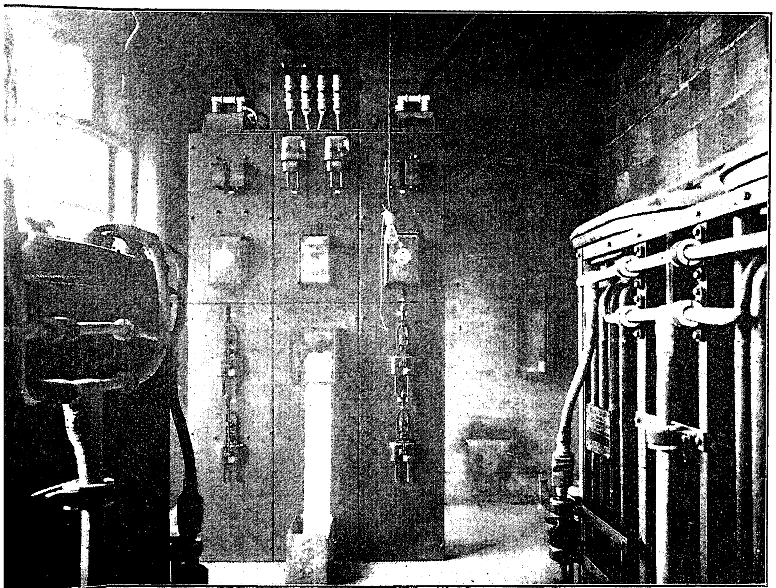

FIG. 9a.—PLANT No. 6 [LIVERSIDGE]

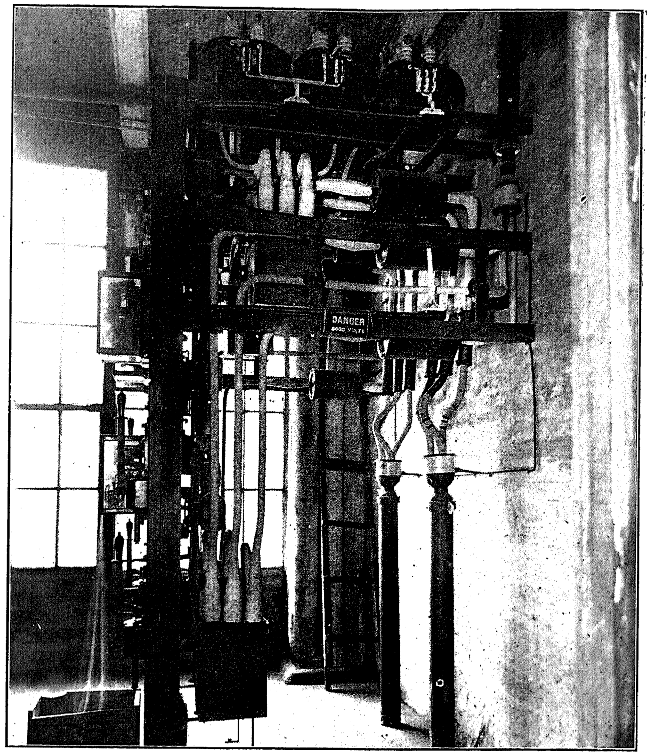

FIG. 9*b*.—PLANT NO. 6 [LIVERSIDGE]

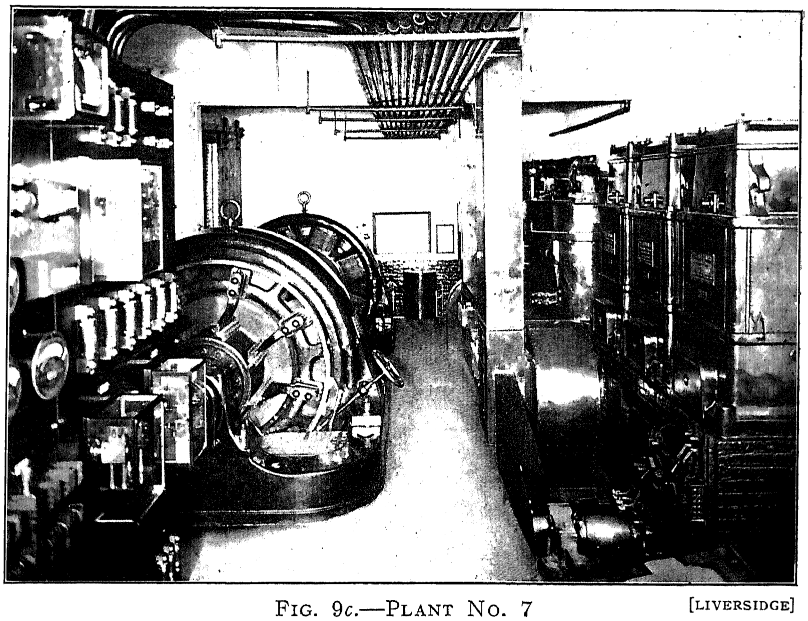

FIG. 9*c*.—PLANT NO. 7 [LIVERSIDGE]

transformers used in connection with totalizing instruments and meters. This line extends to another bus from which is tapped, through automatic oil-break switches, the circuits which supply the two step-down transformer banks. All metering is

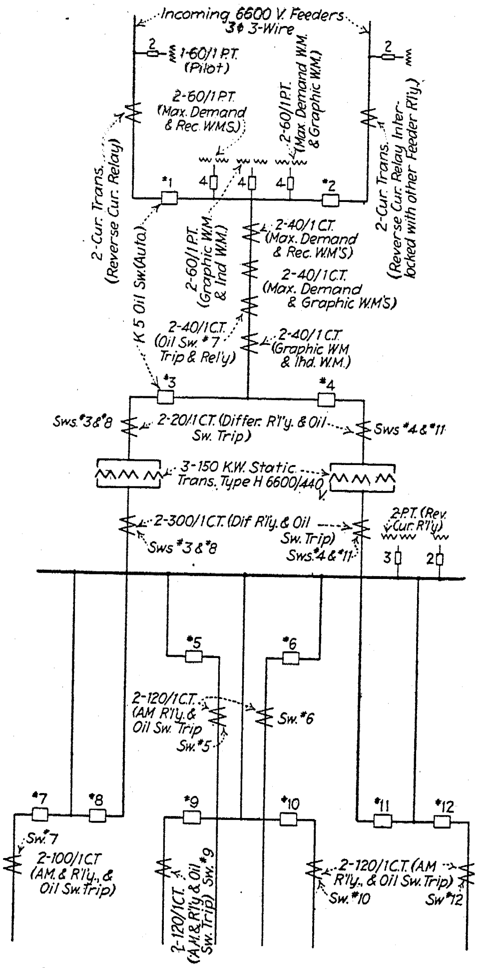

FIG. 9—ELECTRICAL CONNECTIONS OF PLANT NO. 6

done at 6600 volts three-phase, as indicated above, and the two-wattmeter method of three-phase energy measurement is employed.

The consumer's load is supplied at 440 volts three-phase taken from the low-tension side of the power transformers.

The arrangement of both high-tension and low-tension connections in the substation offers many points of interest, and, in particular, the grouping of the six 440-volt, three-phase feeders is to be noted.

Fig. 9 gives single-line diagram of substation connections, Fig. 9*a* shows interior view of substation building and equipment, and Fig. 9*b* is a detail illustration of the apparatus and wiring at rear of 6600-volt switchboard. Attention is called to the special form of porcelain fuse holder for high-voltage fuses on the potential transformers seen at top of switchboard in Fig. 9*a*. This fuse holder covers all live metal parts of the fuse clips, and so assures protection to the substation attendants.

Plant No. 7

Synchronous Converter Industrial Substation of Type Manufacturing Plant. This is supplied with 6600-volt, three-phase current through two incoming feeders.

Transforming equipment consists of two 500-kw. synchronous converters delivering direct-current energy at 240 volts three-wire to the manufacturing plant, and, in addition, two 90-kw. balancers. Total transforming capacity, 1000 kw. Number of direct-current feeders, six. Fig. 9*c* gives a general view of the substation apparatus installed in this plant.

Plant No. 8

Static Transformer Industrial Substation of Manufacturer of Rubber Goods. These goods are for the general trade, and include practically everything from belting and automobile tires down to the finest footwear and office supplies. The load at present is 1000 kw. Steady increase points to 2000 kw. within another year. The working schedule is 54 hours per week.

The consumer built his own substation and purchased all of the transforming apparatus, taking current under a high-tension contract. The operating company furnished the switch cells and switching equipment for the incoming lines, and also provided suitable metering apparatus, but, further than this, has no connection with the consumer's substation.

Energy is supplied by two 13,200-volt, 60-cycle, three-phase feeders brought to a single set of busbars through automatic oil-break switches (see Fig. 10). An electrolytic lightning arrester equipment is connected to the busbars through disconnecting switches. Potential transformers and totalizing

current transformers are connected in the busbars and operate totalizing instruments and watt-hour meters, the two-wattmeter method being employed.

Fig. 11 gives a sectional view of the high-tension switch and busbar structure, and indicates the location of the aluminum cell lightning arrester equipment. Attention is called to the single concrete wall erected parallel to the wall of the building and furnishing the main support of the construction indicated.

The transforming equipment consists of single-phase, oil-insulated, self-cooled power transformers, of which one bank of three transformers is installed at the present time.

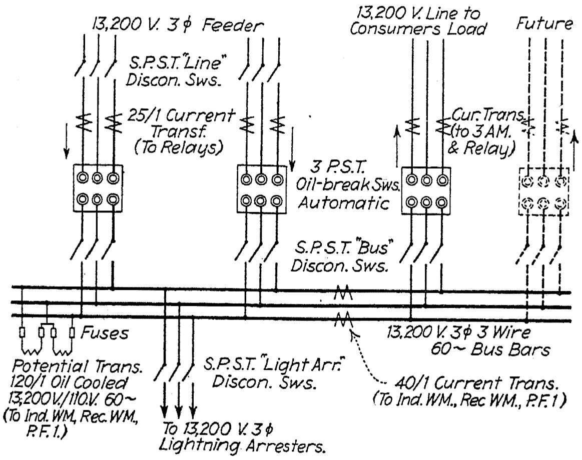

FIG. 10—ELECTRICAL CONNECTIONS TO PLANT NO. 8

Fig. 11*a* shows the general arrangement of the high-tension and low-tension switchboards, together with the transforming apparatus.

Plant No. 9

Industrial Substation Supplying Grain Elevator Equipment and Other Electrical Energy Required on Docks of Railroad Company. The total installation aggregates nearly 3000 kw., of which approximately 600 kw. is maintained exclusively for fire pumping purposes. In general, the equipment is for the operation of the grain elevator apparatus used in loading and unloading cars and for general lighting around the docks.

So far, the operating company has not had a demand in excess of 500 kw., and the hours of service are entirely dependent upon the hours of arrivals and departures of vessels and trains. The

railroad company provided the substation building and operates the station exactly as though it was an isolated plant.

The substation is supplied by three 6900-volt, three-phase incoming feeders, two of which constitute a loop into and out of the station. The loop may be closed or broken independently

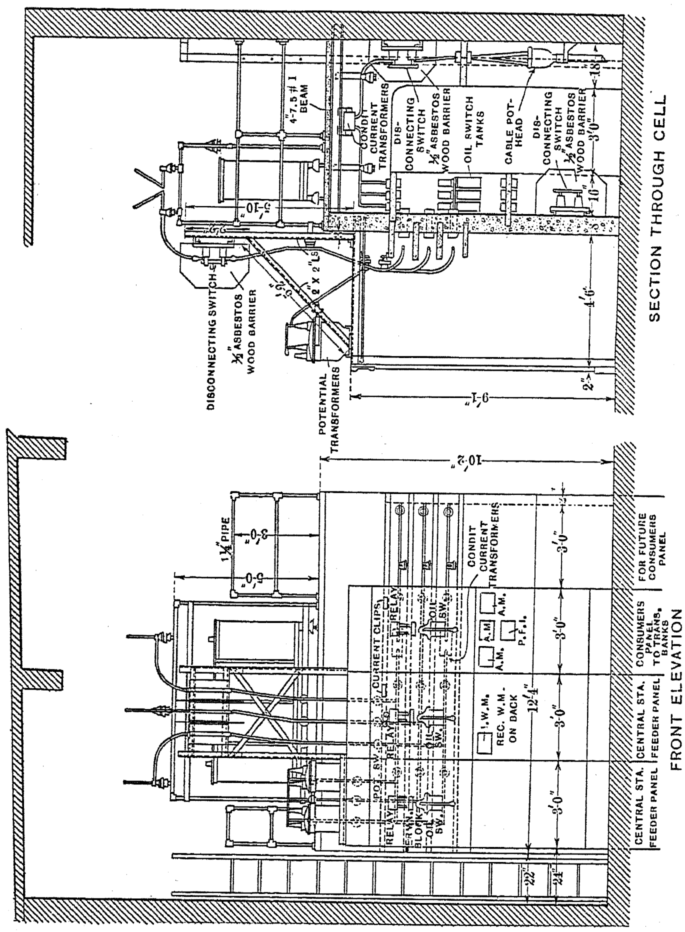

FIG. 11—CONSTRUCTION DETAILS OF HIGH-TENSION STRUCTURE, PLANT NO. 8

of the consumer's busbar by an oil-break switch connected ahead of the line-disconnecting switches of the two feeders.

Three-phase, oil-insulated, self-cooled transformers are used in this station for power service, and single-phase, oil-insulated, self-cooled transformers for lighting. Fig. 11*b* shows the exterior of the substation building, and Fig. 11*c* gives a general view of the interior.

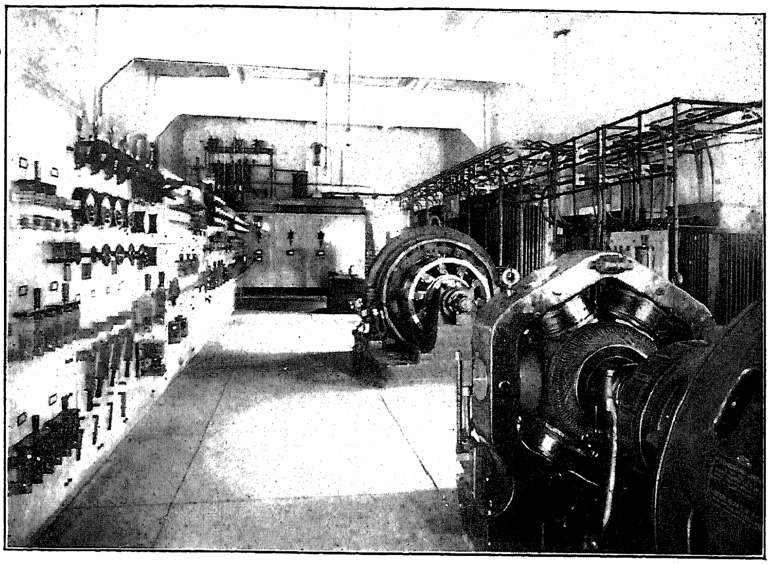

FIG. 11*a*.—PLANT NO. 8 [LIVERSIDGE]

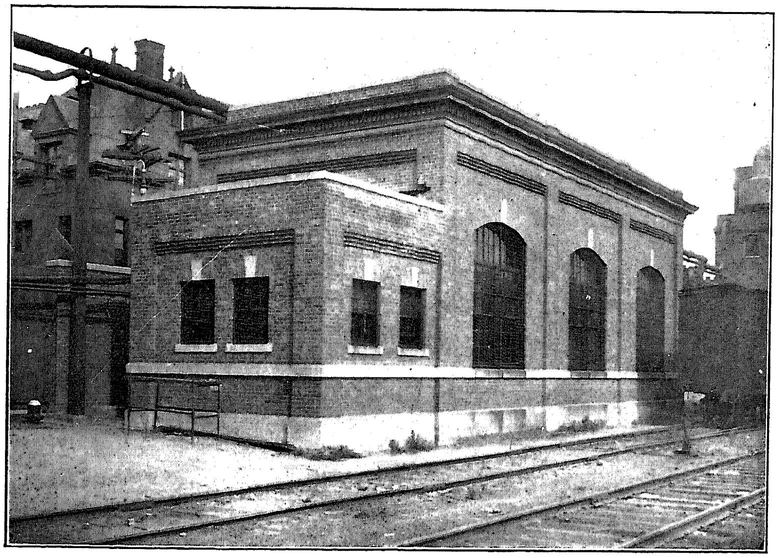

FIG. 11*b*.—PLANT NO. 9 [LIVERSIDGE]

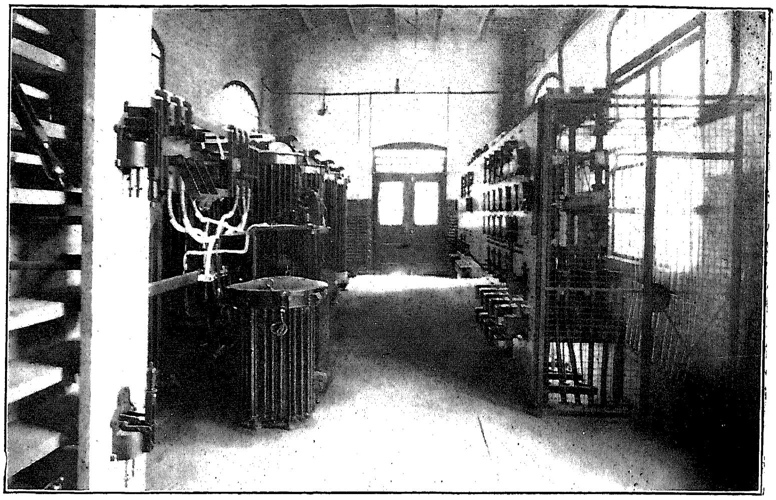

FIG. 11c.—PLANT NO. 9 [LIVERSIDGE]

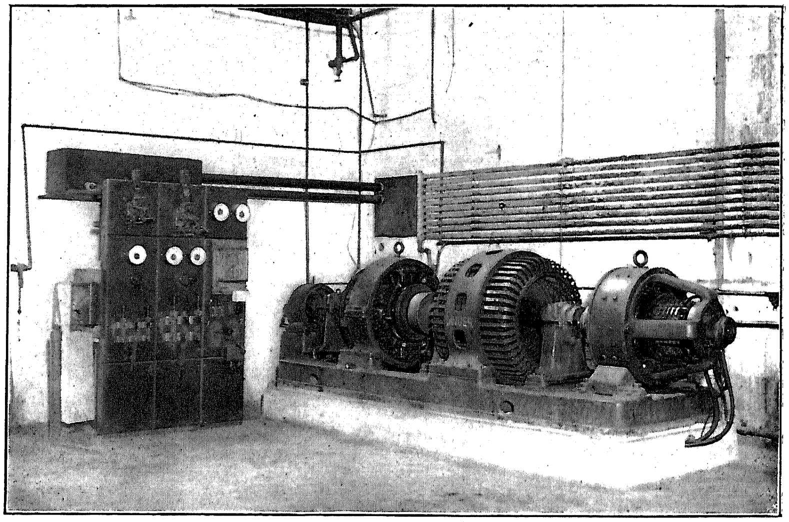

FIG. 12.—PLANT NO. 10 [LIVERSIDGE]

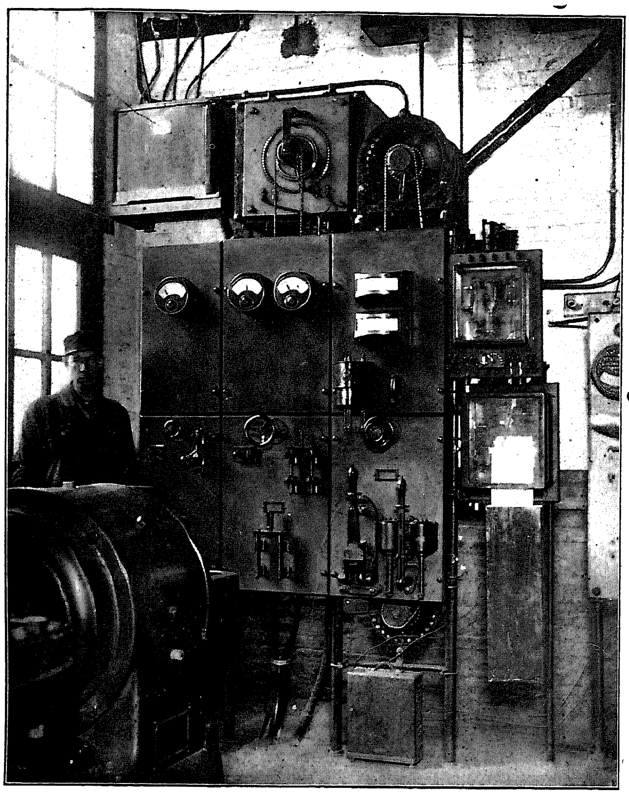

FIG. 13.—PLANT NO. 11 [LIVERSIDGE]

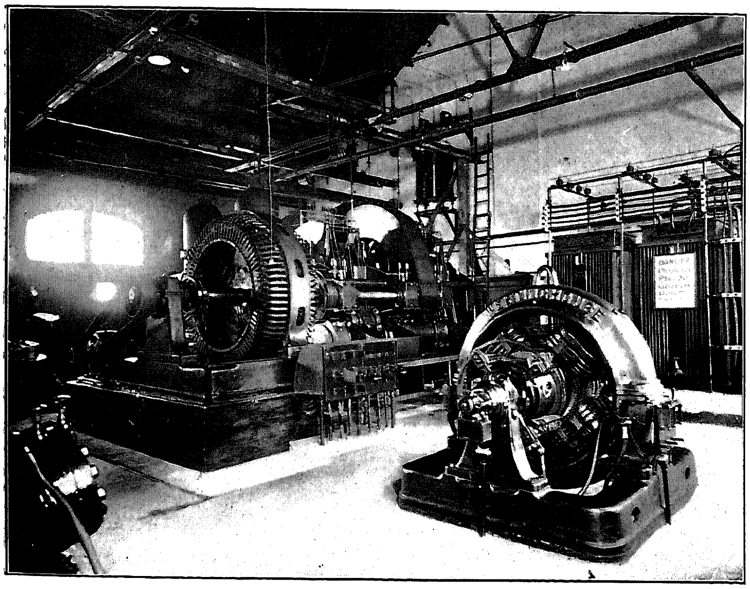

FIG. 14.—PLANT NO. 12 [LIVERSIDGE]

Plant No. 10

Industrial Substation Comprising Vehicle-Charging Equipment in a City Garage. The equipment consists of one three-unit motor-generator set and three-panel control board, as shown in Fig. 12. The motor-generator set consists of one 145-kw., 120-volt, and one 45-kw., 80-volt compound-wound direct-current generator, direct-connected to a 285-h.p., 4150-volt, three-phase, 60-cycle, 900 rev. per min. synchronous motor, with a 5-kw., 125-volt, direct-connected exciter.

The switchboard equipment of the substation includes an automatic regulator used in connection with the synchronous motor and employed in order to maintain constant line potential.

The substation is supplied by a 4150-volt, three-phase, 60-cycle incoming line, feeding directly to the synchronous motor through the necessary automatic oil-break switches and starting compensators.

In order to prevent the charging set taking energy from the truck batteries, should the alternating-current supply be interrupted, the generators are equipped with reverse current relays, set to operate the direct-current circuit breakers on four per cent reverse current.

Plant No. 11

Industrial Substation for Cold Storage Plant. The equipment consists of a three-unit motor-generator set embodying one 90-kw., 250-volt and one 25-kw., 250-volt shunt-wound, direct-current generator, direct-connected to a 210-kv-a., three-phase, 60-cycle, 4150-volt synchronous motor with a 5-kw., 125-volt exciter mounted directly on the end of the shaft.

The substation is supplied by one 4150-volt incoming feeder on which are installed electrolytic lightning arresters and choke coils. The feeder is taken directly to the synchronous motor through the necessary automatic oil-break switches and a three-phase starting compensator for the motor. The motor is equipped with an automatic voltage regulator in order to insure constant line potential.

In this installation it has been deemed advisable to protect the direct-current generator circuits by fuses only, instead of by the usual automatic overload circuit breakers.

The attendance at the plant is good and, while the voltage regulator has given some trouble, the operation of the plant is satisfactory. The load for this class of refrigerating service is very constant throughout the twenty-four hours.

Fig. 13 shows the switchboard at this plant, and one end of the motor-generator set, and indicates the extreme simplicity of the electrical equipment installed.

Plant No. 12

Combination of Synchronous Motor Pumping Station and Small Synchronous Converter Substation: Shown in Fig. 14.

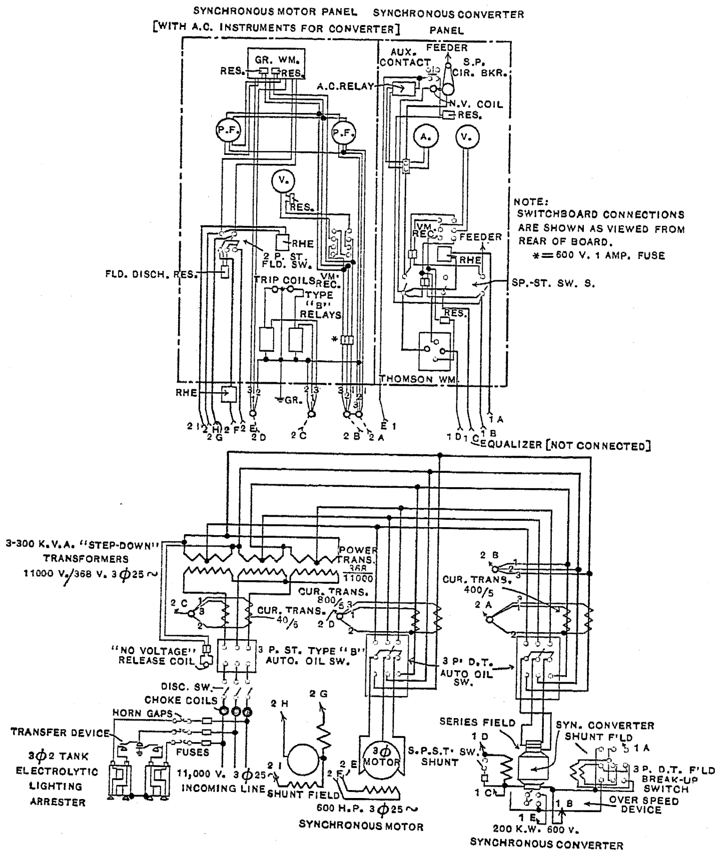

FIG. 15—DETAIL ELECTRICAL CONNECTIONS FOR PLANT NO. 12

This equipment consists of a 600-h.p. pump motor (6,000,000-gallon high-efficiency pump) and a 200-kw. 600-volt railway synchronous converter which feeds a suburban trolley line. The total capacity is approximately 700 kw. Current is supplied at 11,000 volts, three-phase, 25-cycles, on one incoming feeder entering the substation overhead. The feeder is taken

through an oil-break switch, equipped with no-voltage release, directly to a bank of three single-phase step-down transformers which on the low-tension side (368 volts) supply *both* the 600-h.p., three-phase motor and the 200-kw., three-phase synchronous converter.

Both motor and converter are alternating-current starting, from reduced voltage taps on the transformers. A spare transformer unit is maintained in readiness for emergency service. Under agreement between the operating company and the consumer, the operation of the synchronous converter is attended to by the consumer.

The accompanying diagram, Fig. 15, gives the detail connections of the substation equipment.

* * * *

In the descriptions of industrial substations given above, attention has been called particularly to the more important characteristics of design and general construction. At this point it will be interesting to undertake further analysis of those details which have a direct bearing upon the factors to which attention has already been called in the early part of the paper.

These factors may be enumerated again: (1) Space economy; (2) Operating requirements; (3) Fire hazard and safety to attendants; and (4) Cost.

1. *Space Economy.* In all instances this factor should be given careful consideration. Especially is this true when the equipment is to be installed in an already existing factory building, where the consumer has allotted all the space available, and this space permits no latitude in the arrangement of equipment.

Plant No. 3, a synchronous converter substation of four 300-kw. units, is a striking example of the economy which has been effected in this particular. The space provided for the equipment was one corner of an existing engine room which already contained several engine-driven generators, a heavy-duty air compressor, and other miscellaneous power plant auxiliaries. The floor area allotted to the substation equipment measures approximately 30 ft. by 30 ft. (9.14 by 9.14 m.). The height of the engine room permitted the construction of a short gallery upon which was placed all high-tension switching and protective apparatus. This arrangement, while it might not have been selected had a new substation building been erected, neverthe-

less made possible the installation of all apparatus without necessitating any changes in the building construction.

Again, Plant No. 1, which is a static transformer substation, illustrates very clearly the great economies of space to be effected by proper arrangement of the switching and transforming equipment, without impairing, in any way, the efficiency of the design.

Plant No. 10 is also an illustration of an exceedingly compact arrangement of electrical apparatus. In this installation a 285-h.p. motor-generator set and the control switchboard are placed close to the wall of the building. No additional housing was provided in this instance, thereby securing a limited floor area for the installation.

2. *Operating Requirements.* The conditions under which the various equipments of substations operate are often radically different, due to the requirements of the consumer. Careful consideration should be given this point.

One of the important features relating directly to this question is the duration of continuous service, which may vary from a few hours per day to a practically continuous supply. As due provision must be made for inspection and repairs, it is quite evident that, in the case of continuous operation, attention must be given to the proper sectionalization of the apparatus and duplication of equipment. This is indicated in the design of Plant No. 1, Fig. 1. In this case, each individual circuit controlling the incoming feeders and transformer banks is provided with disconnecting switches.

As previously noted, this plant operates almost continuously, and such an arrangement permits of a ready examination of the operating equipment during light loads, without necessitating the interruption of the consumer's service. This type of construction further permits a comparatively simple installation, and obviates the necessity of a duplicate set of busbars and oil-break switch equipment.

In contradistinction to this lay-out, Plant No. 2, Fig. 3, supplying a very intermittent service, is arranged without any means for sectionalization. Provision is made only for disconnecting the single incoming high-voltage feeder from the substation equipment.

Another point to be considered in connection with this question is the operating attention which will be given the installation, either by the consumer or the central station company.

In most cases, however, it is the desire of the consumer to supervise the operation of his equipment, and as a rule this plan is productive of satisfactory results.

It is evident, therefore, that any complications in switching equipment and control apparatus should be studiously avoided.

3. *Fire Hazard and Safety to Attendants.* In connection with this feature, it is interesting to note the tendency toward particular care in construction details as they relate directly to this subject.

Where substation apparatus is to be installed in existing industrial plants, a considerable amount of reconstruction is sometimes advisable. In many cases, the floors and ceilings of the industrial buildings are wood. These should be made fireproof. The usual building alterations consist of the changing to concrete flooring and metal-lined or asbestos-covered ceilings.

In oil-cooled transformer installations, special arrangements are necessary for properly draining the contained oil from the transformer cases. This is accomplished either by pipes connected directly to the transformers or by concrete drains built in the transformer foundations and connected to a common outlet.

An interesting example of this latter type of construction is noted in Plant No. 5, Fig. 8. In this installation, the transformer banks are placed on a concrete base so constructed as to provide a very effectual drainage system for the entire equipment.

The enclosing of high-voltage switchboard equipment to secure the *maximum* of safety to attendants is plainly evidenced in the plant designs to which attention has been called. Asbestos lumber doors and partitions form the more important part of this detail in construction. Besides serving as a protection from accidental contact with high-voltage circuits, these partitions in many cases are excellent barriers for protection from fire.

Plants No. 1, Fig. 2, No. 3, Fig. 4, and No. 8, Fig. 11, may be cited as typifying this feature of construction. A particularly interesting example may be noted in Plant No. 1, Fig. 2, where the high-voltage equipment is entirely enclosed and cannot be reached except by the opening of the several doors composing the enclosing partitions.

4. *Cost.* Not infrequently the central station engineer is limited to a certain minimum expenditure imposed by the prospective consumer, and which in most cases affects the electrical equipment under consideration. It is evident that this limitation may

affect materially the character of the installation; and particularly will this be evidenced in the switchboard and controlling equipment. The changes in this part of the construction are most apparent in the details of control equipment, namely, the type of switchboard, whether marble, slate or open iron frame; the number and type of instruments on the individual circuits, and the character of busbar construction.

These details in many cases are closely related to, and influenced by, the factors already noted.

Nevertheless, there are many points in the design, as above mentioned, that will be directly influenced by the question of construction cost.

Conclusion. In the present paper, all detailed references to costs, and to the economic questions involved in the subject of industrial substations, have been purposely omitted. Furthermore, in the discussion of the plants presented the writer has refrained from all criticism which relates to the question of efficiency in station design.

The attempt has been made, rather, to emphasize how well the engineering design and installation of substations located in consumers' premises, and receiving electrical energy from a central station system, meet the most varied and exacting requirements of the industrial consumer.

* * *

The writer wishes to take this opportunity to express his appreciation of the courtesies shown by the engineering departments of the Commonwealth Edison Company, the Edison Electric Illuminating Company of Boston, the Edison Electric Illuminating Company of Brooklyn, the Rochester Railway & Light Company, and the Philadelphia Electric Company; also to acknowledge the able assistance of Mr. Charles Penrose and Mr. H. C. Albrecht, both of the engineering department of the Philadelphia Electric Company, in the compilation of the paper.

DISCUSSION ON "INDUSTRIAL SUBSTATIONS" (LIVERSIDGE), PHILADELPHIA, PA., OCTOBER 13, 1913.

W. C. L. Elgin: I think Mr. Liversidge has covered many of the important points in relation to substation design, but I have gained the impression that he has paid too much attention to the question of space economy. Although the size of the apparatus readily lends itself in that direction, I think there are many bad designs because too much attention has been paid to obtaining the smallest possible space for the apparatus.

I know of three substations designed for 2000 kw. each; and in examining them, I was impressed with the fact that the principal and only question considered, was apparently to find a place for each piece of apparatus and then to build a wall around it. These substations were only about 20 feet square; and after installing the apparatus there was no room for making repairs. In order properly to inspect any part of the plant that might become defective, it was necessary to go outside of the building, and look into the substation through a window. For this reason, these substations had to be abandoned.

I think the pictures showed that where there was rotating apparatus, reasonable space was allowed, but that the space was smaller where merely static apparatus was installed. In the static substation of 4000 kw. the entire apparatus was installed in a space 30 feet by 10 feet. That space, of course, was ridiculously small. In the next two or three years, I think you will find that this substation will have to be enlarged or otherwise altered.

The cost of the building is relatively small in comparison with the importance of the reliability of service and also with the total cost of the service. The real estate and building costs are practically small items.

One other point in the paper is that of enclosing all the apparatus, especially the high-tension apparatus. I think it should not be enclosed completely, but that partitions, some of which may be made of glass, should be placed around it; or an open space should be provided, of a size sufficiently large to permit of an examination of the apparatus, but small enough to prevent the operator inserting his hands, and making accidental contact. Another advantage of this is that you can locate any trouble in the particular compartment in which it occurs; but if completely enclosed, the smoke will travel from one place to another.

There was another point of which Mr. Liversidge did not speak, and that is the danger, in these cases, from water. It seems to me that substation apparatus should be so designed that it would operate even if completely immersed in water. There has always been a great objection to having water around an electrical installation. I know of a case where a 2400-kw. substation was partially submerged for twenty-four hours and

continued in operation during this entire time. That is an accomplished fact; and we now know that we can operate under these conditions.

I wish to make a plea for more space in substations, instead of space economy.

P. M. Lincoln: Mr. Chairman, I have not much to offer, but I wish to commend the careful thought given in Mr. Liversidge's paper to this question of substations and their design. There has been a great deal of thought given in the past to power stations, but substations and the use of the power therein have been more or less neglected. The substations of the past have partaken somewhat of the nature of "Topsy"—they just grew. I think we are to be congratulated in having someone like Mr. Liversidge, who has given careful attention to this subject, give us the results of his study in a carefully prepared paper such as this.

Mr. Liversidge said the three-wattmeter method was used in some stations and the two-wattmeter in others. Why is that?

What is the method for measuring the maximum demands? Has the maximum demand method of charging come into general use?

Those are some of the questions which occur to me at this time in connection with Mr. Liversidge's paper.

John Mathews: I have noticed that in many of the cases which Mr. Liversidge cited, they use single-phase transformers rather than the polyphase units. The cost of the polyphase is less than the cost of the single-phase unit and the space occupied may be less.

Were there any other features which made the decision in favor of the single-phase unit?

G. W. Brooks: I note in Mr. Liversidge's paper that in the majority of cases installations include two banks of transformers, one of these being spare. It would seem that this is a greater expense than necessary, as reliable service can be secured by the installation of four single-phase transformers, one transformer to be held as spare. This saves the cost of two complete transformers.

In metering power when service is given through two incoming feeders, is it not practical to install current transformers in each of the two incoming lines and connect these transformers in multiple to the same watt-hour meter?

Is it considered desirable to install overload relays on each incoming line feeder where reverse energy relays are used and protection is secured by overload relays on oil switches serving apparatus connected to substation bus?

W. C. L. Eglin: Thinking over some of the remarks I made earlier this afternoon I thought I might possibly have given the impression that I was criticising that portion of Mr. Liversidge's paper regarding space economy. What I wanted to say when I made my statements, was that the apparatus lends itself to

space reduction so well, that that feature is generally abused and the space cut down very much below reasonable limits.

P. V. Stephens: This paper is one of great interest to designing engineers, and there is one point not strongly emphasized in comparison with these other points which have been enumerated. That is, that in addition to the space and the general design, etc., the controlling idea in the design of the substation, especially the industrial substation, should be the continuity of the service that is to be supplied. In other words, in larger installations you will find that this is of prime importance, and it is one of the reasons why a great many of the companies prefer to have their own power and pay more for it, than to run the risk of being shut down because they are depending on one or two feeders.

If you will present to them a lay-out which will guarantee a continuity of service you will go a long way toward getting them to use central station service. One way is to have as many sources of supply as possible. Have at least two feeders from the company's power station to the users, and a two-bus substation system has many advantages. By providing two-way switches on the feeders you can switch on to either bus. This gives a flexible arrangement and greatly decreases the possibility of a shut-down, thereby providing a continuity of service which is a very important factor in supplying power to industrial plants and especially very large plants.

For instance, in the case of a ship-repair plant where a great ship is on the dock to be repaired, and there are heavy overhead and docking expenses all the time the ship is in dry-dock (and to this expense must be added the loss of business), a condition often necessitating a day-and-night job, you can readily imagine what the cost must be in the case of unnecessary delay on an important ship where the steamship company is deprived of its service. You cannot then afford to have a shut-down; and it was on such a proposition in Brooklyn, New York, where I had to design an electrical installation of that kind, that it was necessary for us to give them a positive guaranty of no shut-down on their extensive equipment, and for the last six years they have run continuously without losing a day or night on an equipment of 3500 h.p. in electric motors. But they would have had trouble on four different occasions due to carelessness or accidents, if I had not had the two-feeder, two-bus system in operation.

Charles Penrose: In further extension of the remarks of the previous speaker I ask Mr. Liversidge whether in the design of such substations use cannot be made of bus-sectionalizing switches on single-bus systems in order to insure continuity of service, rather than the necessity of a *double-bus* system such as has been suggested by the immediately preceding questioner? For these reasons: the double-bus lay-out incurs double initial expense, which is undesirable from the point of view of investment, re-

quires increased upkeep and adds to the complexity of operation. The latter is one of the important points which Mr. Liversidge has tried to bring out in his paper this afternoon, namely, the desirability of freedom from those complexities which may spell "trouble" in the operation of the substation.

In regard to the particular interest which Mr. Liversidge's paper has had, at least for me, I would say that it was my good fortune in connection with Mr. Albrecht to be asked by Mr. Liversidge to assist in a small way in the preparation of the paper, and that it has occurred to me more than once what great wealth of material for a paper is offered at this time by the industrial substations already in service in this country. Mr. Liversidge, because of the limitation of space and time, had to restrict his remarks to some 12 stations, which are in operation in different American cities.

The possibilities that are open for further investigation of industrial substations throughout the country are almost limitless, even if consideration is given only to the larger installations. The engineering characteristics of industrial substations have reached the point where the proper design of these plants is comparable to the design which enters into the installation of large central station substations.

But Mr. Liversidge has drawn clearly the line of demarcation between what apparatus should be installed in industrial substations, and what apparatus may not be permitted because of lack of space and complexity of arrangement.

A contrast of the 12 substations which were discussed shows many points of difference in the voltages, phase and frequencies of the sources of supply. The several plants included static, synchronous converter, or a combination of both kinds of equipment. All of these points could only be dwelt upon fully in a very long paper.

The point I want to bring out is that the subject is one of very great importance due to the tremendous development we now have in electrical installations in consumers' premises, where, as I have already said, you may have a substation whose equipment is comparable in many cases to that of the largest substations in those of the larger central station systems.

Harold Goodwin, Jr.: The previous speakers have laid emphasis on the question of continuity of service, particularly with regard to emergency services. Yet I should not like this discussion to go down as unqualified endorsement of emergency services. It may be necessary in some cases, but in other cases the expense might not be warranted. Even if the central station puts it in, the consumer has to pay for it in the end, and this militates against low rates.

The necessity for emergency service depends largely on the value of continuity of service. No one has been able to evaluate this, but the ratio of cost of current to total operating expenses has been found a fair indicator of it. It would be interesting if this

ratio could be added to the data on each plant mentioned in the paper.

H. P. Liversidge: In reply to the points brought out by Mr. Eglin relating particularly to the subject of space economy, I would say that I thoroughly agree with him in the matter of greater space for substation lay-outs. The point that is desired to be emphasized is rather that the space allotment is usually a minimum, due primarily to the fact that the question is often decided before the engineer is asked to consider the installation of the equipment. In most cases this space is too small to be at first considered, and only after considerable effort on the part of the operating company is enough space given to permit of a satisfactory installation. It is quite evident, therefore, that such a condition usually results in a lay-out occupying the extreme minimum of building space.

Replying to Mr. Lincoln's question concerning the two-wattmeter or three-wattmeter method of measurement, I might say that while the two-wattmeter method is perfectly correct, there are practical considerations which arise in operating conditions where the three-wattmeter method is to be preferred.

Referring to the installation of spare transformer units, I would say that, under certain operating conditions one additional transformer will be sufficient for replacing any of the regular operating transformers in case of repairs, etc. Where an interruption of service due to transformer breakdown would be serious, however, it would seem better practise to install a complete duplicate installation of transformer units and switch board equipment.

The subject of continuity of service is one that is of interest to all. The question of duplication of switch and busbar equipment to insure greater reliability of operation, however, under certain conditions is doubtful. For normal capacities, modern switchboard construction has reached that state of development where the danger of breakdown in the busbar or switching equipment need not be seriously considered. It would seem, therefore, that the best installation is that which embodies simplicity in its arrangement rather than the duplication of equipment to insure continuity of operation, in the event of switchboard failures. Where continuous operation is necessary, proper installation of section switches in the busbar and busbar taps will obviate the necessity of complete duplication of buses and switch gear and will permit of a ready examination of the operating equipment.

A paper presented at the 287th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1913.

RELATION OF PLANT SIZE TO POWER COST

BY P. M. LINCOLN

That a large plant can supply a given power service as a part of a general power supply business more economically than a plant of only sufficient size for that given service, is so manifest that most engineers are ready to admit it without argument. However, every isolated plant that is installed where central station service is available is, to a certain extent, evidence that there is somebody not yet convinced of this general truth; consequently a discussion showing why this general statement is true may not be out of place.

There are three distinct reasons why a large plant can take care of a given service more economically than a small one. These reasons are:

1. Because the first cost per kilowatt of the large units entering into the construction of a large plant is lower than of the small units entering into the construction of a small plant, thereby reducing the first cost of the apparatus necessary for the given service and, therefore, reducing the annual fixed charges thereon.
2. Because a large plant inherently can be operated more economically than a small one, and because, further, the large plant can afford to introduce economies which would be out of the question in a small one.
3. Because of the existence of diversity factor, whereby one kilowatt of capacity in a central station will serve a combined load that would take considerably more than one kilowatt if each part of that combined load were to be served separately.

Further discussions of these three reasons will be taken up in the order named above.

1. Relation of Size and First Cost

A large plant will cost less per kilowatt than a small one. This is simply a specific statement of a general law. The larger the amount involved, the cheaper each unit becomes, no matter what the commodity may be: Kilowatts come cheaper when purchased a thousand in one machine than when bought singly; just as cigars come cheaper by the box, or freight rates are lower by the car load.

Although this law is usually recognized qualitatively, few engineers have an adequate conception of how much it means quantitatively. To give some idea of the extent to which this reduction in cost occurs, a number of curves are given herein showing approximately how much the size affects the cost per kilowatt of some of the types of apparatus that enter into the

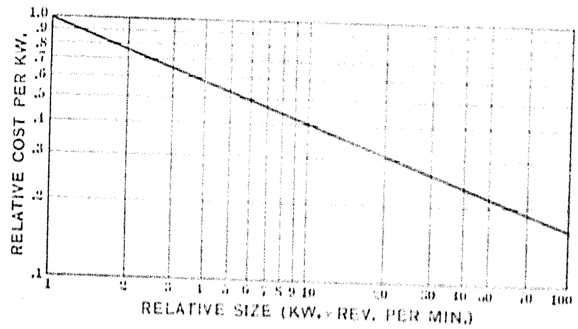

Fig. 1

make-up of a power station. In giving these data, logarithmic cross-section paper is used for two reasons; first, because the range of the data covered in a given curve may be thereby increased, and second, because the law connecting size and cost per kilowatt usually takes an exponential form, thereby enabling us to represent the relation by a straight line on this kind of paper.

Fig. 1 gives data of this nature upon electric generating apparatus. In apparatus of this kind, a variation in size is almost invariably accompanied by a simultaneous variation in speed, and both speed and size have an important influence upon the cost per kilowatt. It is quite possible, however, to take cognizance of the speed variation as well as the output variation and to derive a law that couples the cost per kilowatt with both output and speed. The data given in Fig. 1 are the result of

the inspection of a considerable number of electric generator costs. This curve shows the relative variation of cost per kilowatt as it depends upon size and speed of generator units. An inspection of the curve will show, for instance, that if the speed

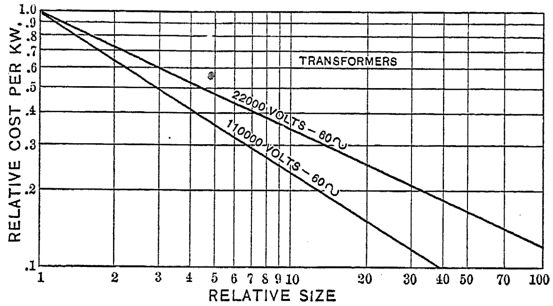

FIG. 2

remains constant the cost per kilowatt will decrease by approximately 65 per cent for an increase of ten fold in the size of the unit.

In Fig. 2 similar data are given for some typical lines of transformers.

In Fig. 3 data are given upon the relative costs of different sizes of boilers.

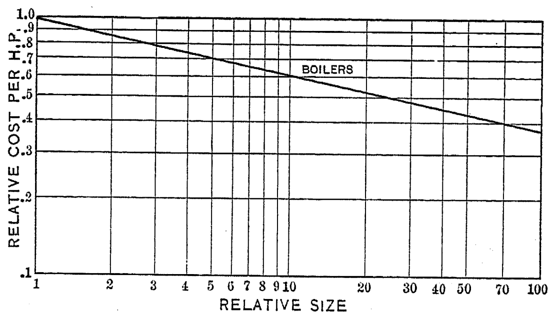

FIG. 3

In using any of these curves it must be borne in mind that a curve is simply a method of stating a general law and that no such general law can take cognizance of an unusual condition. For instance, if we tried to extend the curve for 110,000-volt transformers so as to obtain the cost of a one-kw. transformer, the result would be absurd. When an engineer has designed the

smallest possible transformer suitable for use on 110,000 volts he will necessarily have a transformer of a capacity very much in excess of one kilowatt. In other words, it is impossible to design a transformer of so high a voltage and so low an output. As a consequence, therefore, the use of these curves to obtain relative costs for such conditions would lead to a result which is sadly in error. Common sense must be used in the application of these data.

Comparing a large central station suitable for delivering power for every purpose with the size of a plant that an individual customer of that central station would have to install, if he supplied his own wants, we will find, of course, that the central station plant will be very much larger, anywhere from ten to a thousand fold, possibly even more. However, in comparing complete plants with such a difference in size, we will find that we do not realize the whole of the difference in cost that would be indicated by comparing difference in the cost of the individual parts. The reason for this is that the large plant is inherently more elaborate than the small one. A large plant will naturally be equipped with such items as mechanical stokers, coal and ash handling machinery, coal bunkers and storage yards, superheaters, economizers, condensers with all their auxiliaries, double sets of busbars, distant control electrically operated switches, heat-insulating lagging on all boilers and steam pipes, feed water heaters, water softening plant, etc., some or all of which items may be omitted from the small plant. Although such items cause an increase in the first cost of the large plant, they still do not run its cost up to be as much per kilowatt as the small plant not equipped with these refinements. In the large plant the first cost of these items is more than offset by the operating cost which their use will save and that fact accounts for their use. On the other hand, as the size of the plant is reduced, the point is approached where these cost-saving items may one by one be eliminated, owing to the fact that their presence will lead to a greater resultant cost of power than their absence. It is only where power is produced in relatively large quantities that these various cost-saving devices will pay. This matter will be treated further under the next heading in this paper.

Another saving which would be effected by concentrating power-producing apparatus at a single point instead of distributing it throughout the premises of the various customers served is the tremendous aggregate saving in space. As the size of the

units increases, the saving in space occupied becomes marked. For instance, a 10,000-kw. turbo-generator does not take up anything like ten times as much space as a 1000-kw. generator. In fact the space occupied is but little more than for a 1000-kw. unit, and when we compare the space occupied by a 10,000-kw. unit with a 100-kw. unit, the discrepancy is still more marked.

The aggregate saving in space occupied in housing of plant and in the auxiliary equipment will evidently amount to a large item and the comparison of central station power versus individual plants will result in a very material reduction in the first cost of the former compared to the latter.

2. Economies Due to a Large Plant

The reduction in first cost per kilowatt of a large plant over a small one is by no means the only economy from the concentration of a large amount of power generating apparatus at one point. In fact the reduction in first cost is only a small part of the total saving that can be obtained by such a move.

The total cost of power may be divided into two parts; viz. first annual fixed charges (interest, depreciation, taxes and insurance), that depend upon the first cost and second, operating costs (fuel, labor, repairs, supplies, and superintendence) that are almost entirely independent of the first cost. We have just seen that size has a considerable influence on the first of these divisions and now we propose to show this influence is still more marked on the second division. The proportion that fixed charges enter total power costs is usually somewhere between 30 per cent and 60 per cent, being smaller with small plants. The reason that fixed charges increase in proportion as the size of the plant decreases is not on account of the inherent decrease of this item (because, as we have already seen, it really increases) but because operating costs increase with decrease in size much faster than do fixed charges.

A preceding paragraph of this discussion has called attention to the fact that the larger the plant, the greater refinements it can afford to install. The first matter that requires attention as the size increases is usually the matter of fuel saving. In large plants the cost of fuel usually amounts to somewhere between 50 per cent and 75 per cent of the total operating expense. Obviously, therefore, the fuel bill offers by far the best target when one goes hunting for economy. In plants of small output the fuel bill bears a smaller proportion to the total, not

at all because of better economy but because the other expenses, such as labor, superintendence, etc., go down slower than does fuel as the plant size decreases.

The condenser is undoubtedly the most important piece of apparatus so far as fuel economy is concerned. A large plant is almost invariably placed where suitable condensing water can be obtained, whereas a plant for serving the individual customer has to go on that customer's premises and even if the expense of a condenser is warranted, in a great many cases suitable condensing water is not available except at a cost which makes its use prohibitive. The inherent fuel economy of condensing units as compared with non-condensing units is nearly in the ratio of two to one and it can, therefore, be seen at once how large a factor the condenser becomes in the matter of economical operation.

As the plant increases in size we soon come to a point where an investment in superheaters and economizers will begin to pay. The economy effected by these devices in a large plant is of the order of about 10 per cent of the fuel. When our fuel bill is of the order of 50 per cent of the total cost of power, it is evident such a saving will justify a very considerable expenditure. As the plant output grows smaller, however, the fuel bill becomes a constantly decreasing proportion of the total cost and at the same time the relative cost of superheater and economizers increases, so that we soon arrive at a point where their installation will no longer pay. It is only the plant of comparatively large output that can afford to use this economy.

Uniformity in fuel supply is another item which is of very considerable importance, as is realized by those who have been obliged to change the quality of fuel fired from time to time. The grates, draft, combustion chamber, etc., suitable for one kind of fuel may not be at all suitable for another, and the insurance of a uniform fuel supply is not within the power of the user of fuel in comparatively small quantities. It is only large plants which buy fuel at wholesale that can afford to have a guaranteed and uniform supply. The purchase of fuel under specifications is a refinement in fuel practise that has come into very considerable vogue within the past five or ten years. It is only such plants as use fuel in large quantities that can avail themselves of the uniformity of fuel supply which the purchase of fuel under such specifications will insure.

Some of our larger central stations have found that uniformity in the size of the particles of fuel has an important bearing on

the economy with which it can be burned under boilers. In some plants it has been demonstrated that it is economy to screen the fuel so that dust and small particles may be separated from the larger and burned in a separate furnace particularly designed with that end in view. It is evident that only a plant having a comparatively large fuel consumption can afford to enter into such a refinement in the use of its fuel. Here is another economy that is available only in a larger plant.

After fuel, labor is the next largest of the items that go to make up operating cost. In the large plants it is possible to introduce labor saving devices, that would be out of the question in the small plant. Probably one of the greatest labor saving devices in the modern power plant is the mechanical stoker. Not only does the mechanical stoker save labor but it also gives an ability to force boilers to a point not possible with hand firing. Thus an indirect saving comes from the use of mechanical stokers (in reducing boiler equipment necessary during peaks) that is as great, if not greater, than their effect in the direct saving of labor. In the small plants the installation of mechanical stokers is not justified, because, even with hand firing the boiler room force is so small that it could not be further reduced by introducing stokers.

Again, when we come to analyze engine room labor, it is evident that a 10,000-kw. turbo-generator does not require much more attention than a 100-kw. unit. Each unit has about the same number of bearings and there is little inherent reason for the large unit requiring much more attention than the small one. When we compare them on a per kilowatt basis, the large unit, of course, has a tremendous advantage in labor cost.

In a small plant we will find that the coal supply is brought in from the coal pile in a wheel-barrow and shovelled into the furnace by hand. In the large plant the incoming coal is dumped by gravity from a hopper car and carried almost automatically by machinery into bins above the furnaces where it is fed by gravity to the grates. The difference in labor is, of course, very marked, but it would be ridiculous for the small plant to attempt to use such coal-handling machinery, because the amount of labor which it could save would not begin to pay for the fixed charges on the machinery.

The removal of ashes is another point wherein the large plant has an advantage on account of its size. The small plant must have them raked out by hand, loaded into a wheel-barrow and

hauled away to a pile that is again moved by hand when a sufficient amount has accumulated. The large plant dumps them into a tram-car that takes them directly to a hopper car for disposal at once.

Another item of economy which can be exercised by the large plant, but is prohibited to the small one, is that of adjusting the apparatus to the load to be carried. A large plant usually is equipped with a comparatively large number of units and can operate them so that the units are run near their maximum economy point. On the other hand, a small plant is usually equipped with a relatively small number of units and must often run a unit considerably larger than necessary to take care of the load and consequently operate it at a relatively low point on its economy curve.

And so one may go on indefinitely and enumerate the advantages and economies of the large central station. If the boiler feed water is bad, the large plant can afford to install a water softening plant; the small plant cannot think of such a refinement. The large station can afford to insure itself against a coal miners' strike by installing a coal storage yard, and to insure itself against electrical breakdowns by spare units, spare cables and a double set of buses—refinements that would be entirely out of reach of the individual small plant.

It is evident, therefore, from the foregoing analysis, that not only does the central station have an advantage in first cost but that it has a much greater advantage both in operating cost and in the ability to insure continuity of service.

3. Diversity Factor

Now we come to the third advantage of the large central station serving a diversified load. As the name indicates, diversity factor might be defined as the advantage in capacity which is secured by the large plant serving many different kinds of loads over the aggregate capacity of the many plants that would be required to serve each individual part of this load separately. Not only is the large station cheaper per kilowatt than the small one, but also the large plant does not have to have as many kilowatts of capacity installed to take care of a given aggregate load as would individual plants for taking care of the same service.

The diversity of two or more loads may be complete or only partial. Diversity may also occur on account of either yearly

or daily fluctuations in the time that the maximum of a given load occurs. As an example of yearly fluctuations we might cite, as summer loads, ventilating fans, irrigation, pleasure parks and ice making; as winter loads, electric heating (as for street cars and houses) and electric lighting during the early hours of the daily lighting period. As examples of diversity factor due to daily variations we might cite power for the operation of factories during the day and the power required for illuminating the streets at night. These are examples where the diversity is nearly, if not quite, complete, as there is no coincidence whatever of the times at which such loads must be carried.

Partial diversity is always secured between two loads unless the loads vary in exactly the same proportion at exactly the same time. Such a coincidence is impossible, and as a consequence any loads will have some diversity in the times at which their maxima will be taken.

One of the best examples of diversity that the writer knows of is the use of one of the United States Government irrigation plants in the west for house heating during the winter months—a use which was called to my attention by Mr. O. H. Ensign, Chief Engineer of the United States Reclamation service. The power plant in this case was installed primarily for the purpose of pumping water for the irrigation of some of the arid lands of Idaho. The irrigation season in Idaho opens in April and closes usually in September, operating for this purpose only during the summer months. During the winter months there is ample water to run the plant and practically the only expense of its operation during the winter is the labor necessary for attendance. It is evident that the machinery will have less depreciation if operated during the winter months than if simply shut down and left uncared for. There is not the same chance for the apparatus to absorb moisture and it will unquestionably be in a better shape for this operation than if not operated during the winter.

In this Idaho irrigation district, advantage is taken of this condition by supplying electric heat to the farmers during the winter months at a price that will simply pay the cost of operation. This policy results in a price of the order of one-tenth cent per kw-hr. With such a price, one dollar will buy 3,420,000 B.t.u. With coal running 10,000 B.t.u. per lb. and selling at $4.00 per ton (which is certainly a favorable statement of the fuel conditions in this district) one dollar will buy 5,000,000 B.t.u. An

efficiency of 50 per cent is certainly all that can be expected in burning fuel for house heating purposes, while with electric heat one cannot avoid an efficiency of 100 per cent. As a consequence, we have the condition where the farmers of Idaho are able to heat their houses by electricity actually cheaper than by coal, to say nothing of the greater convenience and cleanliness of the electric method of heating—and this all comes on account of the existence of diversity factor.

Complete diversity occurs only with certain limited kinds of service; partial diversity occurs on every kind of service. The amount of partial diversity which occurs depends entirely upon the nature of that service. Mr. H. B. Gear, in an interesting paper read before the Chicago Section of this Institute in 1910, gives some valuable data on the question of diversity factor. He found, for instance, that in residence lighting the diversity factor amounted to over six, that is, the sum of the maxima of a considerable number of residences was over six times as great as the maximum required from the generating station to serve all of these residences. For commercial lighting, that is, the lighting of retail stores, etc., he found a diversity of nearly $2\frac{1}{2}$; for small scattered service he found a diversity of practically the same figure and for large users the diversity was still 1.4. Possibly this last figure is the most significant of all. It is the large user who would be tempted to install a plant for his own operation. Residence lighting and small scattered power, etc., use such a small quantity of energy that there is practically no incentive for such users to provide their own power. However, the fact that the large user still has a diversity as high as 1.4 is, of itself, sufficient to enable a large central station to supply power to such users cheaper than they can make it themselves. This one consideration, independent of the others that are discussed in this paper, is sufficient to justify the central power station, because it means the installation of less than three-fourths the amount of apparatus in a central station than it would require in separate individual plants for giving the same service.

Even where various services are of the same kind there is a considerable amount of diversity. Mr. Samuel Insull, in an interesting and instructive paper read before this Institute in April, 1912, has shown this to be true. He finds, for instance, that the diversity for the operation of the various steam railroads centering in New York is of the order of some six or eight per cent. When it is borne in mind that this is the diversity for the same

kinds of service, it is evident that the diversity between different kinds of service will be very much greater. It is important, therefore, that a central station diversify its service just as far as possible. For instance, a plant whose main business is to supply lighting and general power can take on a railway load more economically than can a plant whose output is already being taken by railroads. On account of the diversity between these different types of load, the addition of a railway load may be assured by a plant already carrying a general power and lighting load with the addition of less apparatus than required by a separate plant to serve the same load. Concentration of power supply makes for economy in every aspect.

There are two arguments that may, with reason, be urged against the central station method of supply. The first is that the central station requires the addition of a transmitting and distributing system before its customers can be supplied, and the cost, upkeep and losses in this transmitting and distributing system must be added to the central station to make it compara-able with individual customers' plants. This argument is entirely legitimate, as far as it goes, but it does not go far enough. The cost and losses of the transmitting and distributing system do not amount to enough to begin to offset the advantages on the part of the central station that have been detailed in the preceding pages. It is, of course, possible to imagine a condition where the cost and losses of transmission and distribution make the central station supply more expensive than an isolated plant, but this means that we have gone beyond the proper radius of that station. The advantages (in the matter of cost) of the central station are so great that the utmost addition, on account of transmission and distribution, and still maintain good regulation, is not sufficient to permit isolated plants to compete.

The second argument in favor of the isolated plant is that during the season that heating is required the steam may be used twice, once for power and the exhaust for heating. This is also a legitimate argument so far as it goes and its complete discussion requires much more space than I have at my disposal here. In general, however, it can be shown that the advantages which accrue to the centralization of a large amount of power at one point will far outweigh the advantage of the isolated plant even when it is coupled with the heating proposition, as it so often is.

When the isolated plant is used for heating, we must bear in

mind that there is a large part of the year, certainly more than one-half of it, when no heating whatever is required and during this period the plant must accept the losses which are inherent with the combination of power generating and steam heating plant using the same steam. Another thing which must not be forgotten is the daily diversity between the heat and power loads in the isolated plant. Take for example, the case of an office building. The building will, of course, cool off to a certain extent during the night and it is required that it be brought to a certain acceptable temperature by the time the office force arrives in the morning. This will require a considerable amount of steam during the early morning hours, at which period there is absolutely no use for light in the building and practically none for power. The heavy demand for light and power in this same office building will occur just before the force is getting ready to leave for the night and at this particular period of the day the requirements for heat are at a minimum because the heat inertia of the building is sufficient to keep up the temperature at this time, and it is useless to put in more heat at the time when the force is getting ready to leave. Therefore, while it is perfectly true that the same steam can be used economically for lighting and heating, it is impossible to so arrange a combination plant of this kind that the diversity in time requirements for the different kinds of service make it possible to make complete use of this advantage. This is a case where diversity works against and not for economy.

As a result of the foregoing analysis, the writer is of the opinion that there are only two reasons why central stations should not supply all of the electrical service within legitimate reach of their distributing systems. These are, first because the rate offered by the central station does not bear a suitable relation to the cost of the service to be supplied, and

Second, because the prospective customer has some motive other than the cost of the supply for not taking his service from the central station.

DISCUSSION ON "RELATION OF PLANT SIZE TO POWER COST" (LINCOLN), PHILADELPHIA, PA., OCTOBER 13, 1913.

Harry Archer Hornor: Mr. Lincoln has properly stated in the introduction of his paper "that most engineers are ready to admit without argument that a large power plant can supply a given power service as a part of a general power supply business more economically than a plant merely equipped for special manufacturing business." Therefore it is obvious that we should look to other than engineering considerations to find the motives which prevent the prospective customer from purchasing his power from a central station.

The author of this paper presents two arguments that may be urged against the central station method of supply. The first of these arguments, namely the question of the transmission and distribution of power, may easily be dispensed with because of the increasing number of central stations in congested communities, as well as the development in the art of very high potential distribution over long distances. Factories today are rarely placed without the zone of a central station. The promoters of an industrial venture would take into consideration the question of the advantages of such power supply in selecting a site for their plant. I doubt very much whether the central station would have been given as much consideration say ten or fifteen years ago.

The author's second argument in favor of the isolated plant, namely, the use in most industrial companies of steam, must indeed have careful consideration. This argument seems to be the last one which is of direct importance to the engineer. Many industrial plants not only require steam for heating purposes throughout their plant and offices but also employ it in various parts of their manufacture. No doubt the use of steam in this way is extremely uneconomical, and no doubt other forms of energy could be just as well applied. Furthermore, it may be purely because the steam plant is there that steam is so used. Nevertheless the fact that a conversion to some other form of energy must now be made, causes the owner to consider very carefully the cost of this substitution. We see how quickly the problem changes from that of engineering into commercial economics.

Mr. R. S. Hale, in a paper read before a joint meeting of the American Institute of Electrical Engineers and the American Society of Mechanical Engineers held in Boston, February 16, 1910, points out a condition which I dare say would be found in a majority of isolated plants, namely: whereas the central station would figure its cost of power too high the isolated plant would be apt to figure its cost of power too low. This problem would be an extremely easy one and very definite of solution if the isolated plant only manufactured one kind of

power. As a matter of fact the large manufacturing concern, especially one doing a varied business, must equip the plant with many different forms of power. Mr. Lincoln has pointed out that this is exactly the place where the central station can aid because the diversity factor is large and the generating units would naturally be in proportion, making their first cost relatively high. On the other hand the isolated power plant would be under one operating force and under the same accounting system, which would make it difficult in most cases to determine the individual costs of power without a very elaborate system of bookkeeping.

The manufacturing company with which I am connected uses four different kinds of power for its construction purposes, namely, electric, pneumatic, hydraulic and steam. All these forms of power are generated in the same power-house and with the same operating force. It would not be possible to determine definitely the unit cost of any one of these without an elaborate installation of instruments, a special piping system and a particular system of bookkeeping. Let us take the electric power alone: Two double-current generators are daily providing the electric power. These units are rated at 500 kw. and carry a regular load throughout the day of about 600 kw. or 20 per cent overload. They are therefore operated normally at good efficiency as far as the generator is concerned. There is also installed one 500-kw. direct-current generator. This generator is also used for what might be called peak lighting load. The switchboard operator throws the two double-current generators into the distributing system in the morning, shuts them down at noon, places them in service after the noon hour, and shuts them down at quitting time, except in the event of the plant working overtime. This switchboard operator is as a matter of fact an oiler. Since there has been installed a voltage regulator he has no more duties as regards the running of the electric plant than those above outlined. If central station energy was substituted for the electric plant, there would be no reduction in operating force.

Let us consider the problem in another way: The electric power consumed seems to bear a relation, something like 20 per cent, of the total power with the exception of steam. As we would not reduce our operating cost, and could only look for a reduction at the coal pile, the immediate commercial question that would be asked is, would we reduce the amount of coal purchased per year by twenty per cent, and how much money would this represent when we include the amount paid by the year to the central station? For the plant in question, and with the data that is available I am of the belief that there could be no commercial consideration given to this proposal unless the central station could supply electric energy so that no more operating expense to the customer would ensue, and that the cost per kilowatt-hour would be less than one cent. If the plant used

alternating current it would only be necessary to install an industrial substation equipped with static transformers. This would answer the first part of the question. As it happens, approximately one-half the load is direct current, generated at 230 volts, and the other half is two-phase 25-cycle, 200-volt, alternating current. This would necessitate either the conversion of the present plant or the installation of synchronous converters. The power house as now designed would not permit the installation of any additional apparatus, so that parallel operation with the present machinery would only be possible by the erection of a separate building involving a separate operating force.

The next consideration is then, the substitution of electricity for producing all the power, so that the present power house could be completely dispensed with and an electrical substation substituted. This involves a number of interesting considerations into the detail of which it is not possible to fully enter. Briefly, this comprises the question of rotary hydraulic pumps; rotary air-compressors and the question of heating. This latter, though possible of accomplishment by means of electricity, will, I think, be generally admitted to be an expensive substitution, although as Mr. Lincoln has stated the small plant does not reach a point where it pays to install certain economical devices for the production of steam, yet on the other hand there are certain practical economies which can be introduced by which wastes of various kinds, though not entirely eliminated are very much reduced. This makes it problematical in the minds of the owners of such plants, to maintain their plants up to a point where either developments compel a change, or depreciation is so great that the apparatus can no longer sustain the demands put upon it.

It may appear from the foregoing that this is an argument for the isolated plant and against the central station. Such is in no sense the intention. It is rather an endeavor to find the reason which prompts men who own isolated plants to retain them in preference to the purchase of power. The central station may be a little to blame in not making special efforts in this direction.

Granted that they have at the present time accomplished much, I cannot see but what it depends greatly upon whether they wish to accomplish more. If the central station, as Dr. Steinmetz recently stated in an address before the Franklin Institute this month, can find an off-peak power load that does not cost them the installation of more apparatus and additional operating expenses, it is safe to say that the central station could sell its power at even as low a rate as mentioned by Mr. Lincoln in his illustration of diversity factor as shown by the United States Reclamation Service in the Idaho Irrigation System. But if, as we have recently heard it proposed, the central stations take over the power supply to railroads for the electrification

of surburban lines, I do not see but what the central station will be required to install and operate more apparatus, because this load will undoubtedly strike the peak, as the busy people will be going to and from their work at the same time that the station will need to supply its peak load.

This is an interesting subject because it is such a large one and so many different factors enter into every side from which you view it. Although steam central plants have shown a wonderful reliability as well as flexibility, it has not been very long ago that a friend of mine in the northeastern part of this country very seriously considered annulling his contract with a water-power central station, and installing a plant of his own. I believe, however, that it is generally recognized to-day that such central stations, subject by the elements to an interruption of service, must parallel their water turbines with a steam plant, because of this uncontrollable consequence.

I notice that Mr. Lincoln in his paper did not touch particularly upon this point, and I suppose he did not because such eventualities are not so frequent. It is nevertheless a very important motive in any manufacturing concern whose product depends entirely upon the supply of electric current.

As a summary I should deduce the following:

First, the promoters of any new manufacturing venture would today consider the location, and operation of their industrial plant so that central station power could be used. This would be considered in their estimate of first cost, expense of operation, and in their original design.

Second, for those owners who are now operating isolated plants supplying various powers including steam, convincing reasons must be presented whereby they may abandon their present plant entirely and economically purchase their power.

Third, I believe the principal motive underlying the retention of the isolated plant is due to commercial economy rather than to engineering principles.

Fourth, I believe that the central station in its development will overcome all obstacles and reduce the number of isolated plants.

Fifth, I also believe that in the case of very large vessels that a central station adapted for this special service will be installed, and that requisite power will be delivered both for the driving of the vessel and for the operation of her auxiliary machinery.

W. C. L. Eglin: Mr. Hornor seems to take up one or two questions on the other side. There is a fourth point that occurred to me while Mr. Lincoln was reading his paper, and that is, the depreciation of any apparatus. The consumer invariably has his mind fixed on the efficiency shown by his apparatus when first installed and tested; and he still believes it is operating at the same point of efficiency after several years of use. The central station company generally finds that it pays to discard such apparatus and install more efficient apparatus. That is

very clearly shown in all the larger stations; whereas with the individual owner of a small plant, some particular change in his business or the extension of the business to the point where the plant becomes too small for his needs, would be required before he would think of abandoning it.

The next thing is the inertia to be overcome. Take the case of the tungsten lamp: It is three times as efficient as the carbon lamp, yet there are three times as many carbon lamps sold today as there are tungsten lamps. The people are not installing as many tungsten lamps as they should, and it will take from three to five years to educate them to do so. In Europe you will have a task trying to find a carbon lamp. You see them, it is true, but you see many more tungsten lamps than carbon, while in this country you will see more carbon lamps than tungsten.

It is only a matter of time before the central station must be extended to the point where its service will become practically universal.

That is the real objection to the substitution of electrical service from the central station—you must have a property large enough to be able to afford to "scrap" apparatus, even to the extent, sometimes, of removing the entire plant investment from your books. It is hard to get the ordinary manufacturer to throw out his plant and "forget about it."

P. V. Stevens: I ask Mr. Lincoln for my own information, and possibly for the sake of others, this question: The discussion or treatment in this paper has been apparently referring to steam plants, and the majority are familar with the conditions met in such plants, but assuming the advantage of the large central station over a small station is 10 per cent, I would like to know what percentage would represent the advantage in the operation of oil and gas plants where the fuel is relatively cheap.

C. O. Mailloux: This paper discusses the general case very comprehensively and intelligently. When we come to special cases, certain modifications may be necessary in the reasoning and in the conclusions, as the author has himself pointed out. We all agree, for example, in regard to the general statement that the economy of a plant will be a direct function of its size. There are, however, considerations which often argue in favor, and demonstrate the superiority, from a financial standpoint, of a small individual plant—the so-called "isolated plant."

My experience with isolated plants covers a period of over twenty-five years, and it is so diversified that I cannot now give more than a general summary of it. As consulting engineer, I have had, during that period, to deal, in some technical capacity or other, with perhaps a thousand isolated plants, large and small. In more than half of these cases, I have had charge of the design and installation of the plant, and in a number of cases I have also had charge, for a time at least, of its operation.

I have also had occasion to make reports in regard to the feasibility and economy of isolated plants in hundreds of cases. In the latter cases, the question was gone into most thoroughly; a very careful, honest attempt was made to get at all the facts and figures bearing on the case, in order to reach the true and correct answer as to whether the plant would pay or not. In many cases, the answer indicated that the plant would not pay; but in many others it showed definitely that the isolated plant was warranted. I will only refer now to those instances where there was absolutely no chance for the central station to replace the isolated plant.

A very interesting case was that of a large sugar refining establishment in Brooklyn, in which a boiler plant of about 10,000 h.p. was rendered necessary because of the immense amount of evaporating to be done incidental to the sugar refining operations. This large boiler plant would have to be there anyhow. The same boiler room force and the same facilities would be necessary whether the electric current supply required for lighting and power came from an isolated plant or from a central station.

At the time this plant was designed, the question of electric current supply received careful consideration, and it was soon made obvious that the cheapest and most practical way would be for the establishment to produce its own power, by generating steam at high pressure, say 150 lb., and reducing this pressure to that which is required for evaporating, namely, from 7 to 12 lb., by passing the steam through a simple engine designed to operate under a back pressure of 7 to 12 lb. Now under those conditions, a simple engine would not be particularly economical, as we know, but looking at the matter from the standpoint of thermodynamics, and considering the amount of energy abstracted from that steam in being thus "throttled" from 150 lb. pressure down to about 10 lb. pressure, while passing through the engine cylinder, one finds that the steam loses only a very small percentage of its total energy, (the actual theoretical loss is only about 3 per cent for the above conditions); and yet in falling by expansion from 150 lb. to 10 lb., it is capable of generating a great amount of power. The plant was installed and was a great success. It has been running more than 15 years, developing somewhere between 1500 and 2000 h.p., through engines operating direct-connected dynamos which supply electrical energy sufficient to operate the lighting system and for all the electric motors of various sizes required in the different buildings. In a case like this the cost of fuel and boiler room attendance are reduced to an insignificant amount. The only items that enter materially into the cost of the electric power are the cost of engine and dynamo attendance, and the fixed charges on the cost and also the maintenance of the engines, generators, dynamo leads and switchboard; and considering the large output obtainable from the plant, it is apparent that the cost of electrical energy per kilowatt-hour must be very

small. That concern is one of the few in New York City that can afford to use electricity for cooking. It literally has electricity to burn. An electrical cooking installation was put in which has been in operation since the plant was started, and which serves daily for cooking the lunch for a large force of men, composed of the heads of various departments. My recollection is that the cost of electric current was somewhere around 2 or 3 mills per kw-hr. It would, of course, have been impossible for any central station plant to compete with such an isolated plant.

There are many other cases where the isolated plant proves to be cheaper for the consumer than the central station current supply. I have found this to be true in scores of cases, as in large office buildings, where steam heating is required during many months. Mr. Lincoln says that no heating is required for more than half the year. My own experience leads me to a different conclusion. In these latitudes, one must figure on heat being required in a building for at least seven months. Most of the time during that period, the fuel consumption which is properly chargeable to the electrical service when high pressure steam is used, and the cylinder of an engine is employed as a throttling valve to bring the steam pressure down to three or five pounds, is small because, as already seen, the energy abstracted from the steam by that throttling process is very small. Even assuming that there may be a certain time during the 24 hours of the day when one must use steam that is not chargeable to the heating system, yet the total cost of the coal and of the boiler room attendance chargeable to the electric service in the winter months is very small. This matter has been investigated by me, or under my direction, in many scores of cases. In some instances we have been able to corroborate the conclusions of our investigations. There were cases where the current had been supplied from a central station and return was made to the isolated plant. In other words, we have had cases where the same building has been operated under the same conditions, both by current from a central station and by current from its own isolated plant. We have also had cases where the steam for heating as well as for power was taken from the central station in New York which furnishes steam to consumers through underground mains. We have been able to make comparisons of cost in instances where an abundance of good and reliable data was available to enable us to check up the results and conclusions very carefully. One interesting instance was the building in which my office was located for a number of years. In this case the isolated plant, after being operated for a certain period of years, was stopped. Electric current was taken from a central station and steam for heating was taken from the underground steam mains. The total cost of the service proved to be considerably higher than expected, and eventually a return was made to the isolated plant, which has since then remained in operation.

A careful study of the facts and figures, taking into consideration every factor bearing on the case, including depreciation, obsolescence, rental value of space, and all like conditions, showed that it cost the building less to produce its own supply of electricity and steam than to take it from the street mains.

I think that Mr. Eglin's remarks in regard to lamp economy have an important bearing upon this situation. It now seems possible that we shall be able to reduce the lighting load of a plant to a great extent with lamps giving a candle power with $\frac{1}{2}$ watt. Under those circumstances, the electric load, especially in buildings where electric current is used almost entirely for lighting, will be greatly reduced. While this does not make much difference in the winter months, yet it will make considerable difference in the summer months, because the expenses which are fixed, such as the cost of labor, interest on plant, etc., then become relatively large and increase the cost per kw-hr. materially. Under those circumstances, the isolated plant, while still effecting a saving during the winter months, might represent a loss during the summer months. I therefore expect that the improvement in efficiency of incandescent lamps will help to bring about the gradual elimination of isolated plants.

I am in accord with the feeling that the number of isolated plants will go on diminishing. It seems to be in harmony with the nature of things, and with the principles which Mr. Lincoln has so clearly set forth in the first part of his paper. I cannot quite assent to the proposition that they can be all eliminated at the present time. It is my belief that there are many, indeed thousands of cases, where the isolated plant is still cheaper than the central station. I would not say, however, that the time will not come when we may speak of an isolated plant as having been relegated to the museum of ancient things.

M. G. Lloyd: As one engaged in a weekly endeavor to demonstrate the desirability and feasibility of central-station service I have been much interested in Mr. Lincoln's paper. He has demonstrated his main thesis, viz., that power can be generated at less cost in a large plant than it can in a small plant, but as he grants in the last two pages of his paper, that is not all there is to the question of installing central-station service.

I am sorry we have not more figures on the question of what the cost of distribution is, as I believe it to be a much more important item than the author has indicated. I think I remember that a representative of the Baltimore central station at one of our former meetings made the statement that the investment in the distribution plant in that city was greater than in the generating plant. In Chicago this is undoubtedly true and the distribution system there has probably cost 30 or 40 per cent more than the generating plant. Consequently the fixed charges on this portion of the investment are greater than the fixed charges upon the investment for power house and there will also be an operating expense for distribution which will

cover the power loss in cables and maintenance cost for this portion of the system. This results in an important item of the total cost which the isolated plant does not have to include in its computation.

One of the standard arguments for the isolated plant is the economy of combining the use of steam for heating and for power generation. Mr. Mailloux has already shown that there are cases where that is sufficiently advantageous to over-balance any advantage the central station may have in other respects. Mr. Lincoln has rather weakened his argument on this point by limiting the period during which buildings require heating to six months; in my territory (Chicago) heating is required for fully eight months. While heating is not actually required every day during this period it is necessary to have steam up and ready to turn on in case of a sudden turn to cold weather. It is true that the load curve for heating is, however, not coincident with the load curve for power, but that does not affect the question of cost so much as the point of whether the peak loads coincide. Mr. Lincoln claims that the heating load in many instances falls off entirely before the power peak comes on between 5 and 6 p. m. This is not true of office buildings, which must be heated well into the evening.

I should like to take exception to one minor point in the paper where diversity factor is referred to. In order to have a diversity factor of unity the author claims that the loads must be proportional at all times. I do not think that statement can be upheld, because even though the load curves may be entirely different in two plants having the maximum in each case at the same time there is no diversity since the generating equipment must be sufficient to supply that maximum and the diversity factor will be unity, although the load factors of the two plants are entirely different.

Central-station solicitors realize that if their business depended only on the three main propositions brought out in Mr. Lincoln's paper they would have no difficulty in getting all the customers that were solicited. Other points have to be met, however, and while it may not have been within the province of Mr. Lincoln's paper to discuss these, still they must be considered with respect to central-station service. His arguments are getting stronger every day, owing to the ever-increasing size of the central station, and its units, which are now up to the point of 20,000 to 35,000 kilowatts. The central-station man can make his case stronger in every instance where he has the best of the argument if he realizes fully the arguments upon the other side and is free to admit that there are cases where the central station cannot compete with the isolated plant.

C. O. Mailloux: I think that the previous speaker overestimates the importance of the increasing size of the central station units. The total cost of delivering the service from the central station is not made up of the central station cost plus fixed

charges, but is made up of the total central station cost plus the cost of delivery. Now the cost of delivery, it happens, is very much greater than the cost of producing the energy. The most that can be expected as the result of increase in size of the units is an economy of a few mills per kilowatt hour. If the cost of electrical energy at the busbars in the central station is, let us say, 55 mills per kw-hr. we may be able to get it down to 45 mills or even to 35 mills. There is an "asymptotic" value somewhere, which is probably between three tenths and four-tenths of a cent. To this must be added the cost of transmission and distribution. The further economies realizable must be effected mostly in the cost of distributing the electrical energy supplied to the consumer, which is never less than 0.5 cent to points nearby, and it may be two, three or four cents to remote points.

It seems to me that we cannot hope for much from the increased economies resulting from the increased efficiencies in the central station. In a case where the bulk of the cost is for electric power (for electric elevators, ventilation, etc.), the conditions will not be more favorable to the central station, but more likely will be less so. The conditions which may make a great decrease in the load of the isolated plant will arise especially in cases where the bulk of the service is for lighting.

J. P. Jackson: Many plants that you would consider competitive in any way, may be so small that it would not pay to put in feed-water heaters, etc. But I judge that with any plant so small that it would not need such auxiliaries, there is no question but that it would be more economical to go to the central station for power. Certainly very small primary power generation units are as a rule very undesirable, when central station power can be obtained at suitable rates.

I would like to emphasize Mr. Eglin's statement about the depreciation in figuring out the cost to an isolated plant. The specialist emphasizes the necessity of improving everything. I imagine the man who puts up the money in the plant sees very dimly that the actual plant is decreasing or depreciating due to the improvement of the art. His plant is running all right, and he does not like to be told that it is depreciating on account of advance in the art.

There is another thing I believe it is worth while to mention specifically and that is the lucid, clear statement of these subjects which our friend Mr. Lincoln uses. He has an extraordinary way of putting things, so that a layman, like some of us, can understand what he is saying. I believe if the engineers would confine themselves to a simple, clear intelligible statement of the principles of science and engineering, that engineering would advance with greater rapidity than otherwise.

Finally, permit me to say that I am on the side of the central station. I believe the central station is bound to be the great source of power in the world; but I also believe with Mr. Mail-

loux, that each case must be studied out on its merits, and no general statement of the facts should be accepted. Mr. Mailloux is right, that buildings having lighting, heating and other loads to carry might be different in their relative conditions from others.

G. J. Blum: It seems to me that the discussion has brought out a point worth considering and that is that the central stations while trying, so to speak, to get nearer to their customer, are in reality getting further away from him. I refer to the concentration of generating equipment in a very few very large power houses which in many cases are located at an average great distance from the points of greatest load, thus entailing high fixed and high maintainance charges on distribution equipment.

A reasonable increase in the number of generating stations so located in reference to load centers as to reduce line losses and cable troubles to a minimum and to make possible an alternative selection at the substations, especially the large industrial substations referred to tonight, in case of trouble on any particular feeder, would in the speaker's opinion make much more remote the possibility of any interruption of industrial service dependent on central station supply. The matter of steam heating service from such central stations would further suggest itself as a possible source of revenue.

I think it is along these lines that thought might be directed by those men responsible for the most profitable operation of the central station.

P. M. Lincoln: The point is well made by Mr. Hornor and Mr. Eglin, that the central station not only must show economy in serving a new customer but that often in the case of an existing isolated plant, the central station must have charged against it the fixed charges on the plant that is displaced by the use of central station power. It is an endeavor to show a saving after a scrapping of the old plant which breaks the back of the central station.

The paper I have prepared necessarily deals with generalities, and contemplates the conditions necessary to compete when no isolated plant exists. When we deal with the conditions of an isolated plant already built, the margin in favor of central station power is much reduced and sometimes wiped out.

Mr. Eglin mentions the fact that carbon lamps were scarcely seen abroad while very frequently used in this country; and I looked at the lights used in this room and I find they are carbon lamps. Here is a case in point where carbon lamps are in use, and where tungsten lamps would undoubtedly save a considerable amount.

Mr. Stevens has asked a question as to the possible competition between central station plants and isolated plants that use oil or natural gas for fuel. The best answer I know of to that is to point to the scarcity of such oil and gas plants. Theoretically the Diesel engine or the gas engine can do better than the cen-

tral station steam plant in the matter of thermal efficiency. However, the handicap against them in other directions is such that they have made comparatively little headway.

Mr. Mailloux cites a case where the central station plant would have no chance at all. His sugar refinery required large quantities of steam for the vacuum pans for evaporating, and there was consequently a large boiler plant, and the small percentage of steam that was taken in generating the power made the power cost comparatively slight. It takes very little more heat to turn out steam at 150 lb. pressure than it does at 15 lb. and the power that can be obtained in throttling down from 150 lb. to 15 lb. is a by-product which costs practically nothing. In that case I do not think central-station power would stand a ghost of a show.

I note my estimate of the time during which heat for buildings is required is questioned. My estimate was based on conditions as they exist in my own house. I start my furnace about October 15th and stop about April 15th. If I should count from the time it is first started to the time when it is last used, it might be somewhat more than six months; but there are warm fall days and warm spring days when the furnace is not required. Now the requirement for heating in the usual building in the main covers about the same period of time. There is a further fact which I did not emphasize in my paper, that the maximum heat requirements for zero weather are tremendously greater than the average. This fact entails a very decided additional difficulty in using the same steam for both heat and power.

In answer to the comments of Mr. Mailloux and other gentlemen, let me point out the first of the requirements I set forth in the last page of my paper; I there call attention to two reasons why central-station power might not be used to supply all of the electrical service within legitimate reach of their distributing systems. The first of those reasons is, that the rate offered by the central station does not bear a suitable relation to the cost of the service to be supplied. I believe that the increased use of central station power that will surely come as time goes on will reduce its cost very considerably from what it has been in the past.

Mr. Lloyd mentions the fact that the cost of distributing central station power is very considerable, which is true. In one case I figured the distributing cost ran from 60 to 70 per cent as much as the cost of the power itself. But that cost enters into fixed charges only. The distributing system "eats no coal" except what may be due to the losses therein, which are comparatively small. The additional cost of central station power on account of distribution is not sufficient, in general, to justify the isolated plant.

Presented at the Chicago Section Meeting of the American Institute of Electrical Engineers, Chicago, Ill., October 29, 1913.

INSTABILITY OF ELECTRIC CIRCUITS

BY CHARLES P. STEINMETZ

During the earlier days of electrical engineering practically all theoretical investigations were limited to circuits in stable or stationary condition, and where phenomena of instability occurred, and made themselves felt as disturbances or troubles in electric circuits, they either remained not understood, or the theoretical study was limited to the specific phenomenon, as in the cases of lightning, dropping out of step of induction motors, hunting of synchronous machines, etc., or, as in the design of arc lamps and arc lighting machinery, the opinion prevailed that theoretical calculations were impossible and that design by trial only, based on practical experience, was feasible.

The first class of unstable phenomena which was systematically investigated, was the transients, and even today it is questionable whether a systematic theoretical classification and investigation of the conditions of instability in electric circuits is yet feasible. Only a preliminary classification and discussion of such phenomena will be attempted in the following.

Three main types of instability in electric systems may be distinguished:

1. The transients of readjustment to changed circuit conditions.

2. Unstable electrical equilibrium; that is, the condition in which the effect of a cause increases the cause.

3. Permanent instability resulting from a combination of circuit constants which cannot co-exist.

(1) TRANSIENTS

Transients are the phenomena which occur at the change of circuit conditions, when current, voltage, etc., readjust them-

selves from the values corresponding to the previous condition to the values corresponding to the new condition of the circuit. For instance, if a switch is closed, and thereby a load put on the circuit, the current cannot instantly increase to the value corresponding to the increased load, but some time elapses, during which the increase of the stored magnetic energy, corresponding to the increased current, is brought about. Or, if a motor switch is closed, a period of acceleration intervenes before the flow of current becomes stationary, etc.

The characteristic of transients therefore is, as implied in the term, that they are of limited, and usually of very short duration, intervening between two periods of stable conditions.

Considerable theoretical work has been done, more or less systematically, on transients, and a great mass of information is thus available in the literature. However, to some extent, the transients of our theoretical literature are still those of the "phantom circuit"; that is, a circuit in which the constants r, L, C, g, are assumed as constant. The effect of the variation of constants, as found more or less in actual circuits, viz., the change of L with the current in circuits containing iron; the change of C and g with the voltage (corona, etc.); the change of r and g with the frequency, etc., has been studied to a limited extent only, and in specific cases.

In the application of the theory of transients to actual electric circuits, considerable judgment is thus often necessary to allow and correct for these "secondary" phenomena which are not included in the theoretical equations.

Especially deficient is our knowledge of the conditions under which the attenuation constant of a transient becomes zero or negative, and the transient thereby becomes permanent, or becomes a cumulative surge, and the phenomenon thereby is taken out of group one and falls under group three or group two of unstable systems.

(2) Unstable Electrical Equilibrium

If the effect brought about by a cause is such as to oppose or reduce the cause, the effect must limit itself and stability be finally reached. If, however, the effect brought about by a cause increases the cause, the effect continues with increasing intensity, that is, instability results.

This applies not to electrical phenomena alone, but equally to all other phenomena.

For instance, if in a motor, by increase of load, the torque becomes less than the load, the motor slows down. If now the decrease of speed of the motor increases the motor torque—as in a series motor—the decrease of speed stops at the speed at which the motor torque has become equal to the load. Thus, the decrease of speed limits itself, and a stable condition is restored at a lower speed. If, however, the decrease of speed of the motor decreases the motor torque—as in an induction motor below the maximum torque point—the decrease of the motor speed causes a still greater reduction of the motor torque below the load, and, therefore, a still greater slowing down of the motor, and thus with increasing rapidity the motor speed decreases until the motor stops; a condition of unstable equilibrium.

Such instability is usually the result of the system; that is, the combination of elements, but is not inherent in any of the elements. For example, in the above instance of the induction motor, while the part of the induction motor speed-torque curve below the maximum torque is often called the "unstable branch", this is true only relatively. If, with the decrease of the speed of the motor due to an increased load, the load would also decrease, and if the load should decrease with the speed at a faster rate than the motor torque decreases, (fans, ship propellers), the decrease of speed would limit itself; that is, the condition would be stable.

To illustrate more fully, in Fig. 1 are shown the speed-torque curves of an induction motor for various values of constant impressed voltage, $e_1, e_2, e_3 \ldots \ldots e_8$.

With a load requiring the same constant torque at all speeds, A, in Fig. 1, the motor could not run at all at voltages e_1 and e_2. At voltages e_7 and e_8 the motor would start and run up to a speed near synchronism, where it is stable. At voltages e_3 to e_6 the motor torque equals the load at two speeds, a_1 and a_2, on the curve e_4. The higher one of these is stable, the lower unstable. From any speed above a_2 the motor speeds up to a_1. From any speed below a_2, it slows down to a standstill. All the speeds below that corresponding to the maximum torque point c_0 are unstable with this character of load and cannot persist, but the motor either accelerates and runs up to above s_0 or slows down to standstill.

With a load requiring a torque proportionate to the speed, B, in Fig. 1 (electric generator with constant field excitation

and constant resistance of load), the motor always starts, but for voltages e_1 to e_3 never can run above a low speed (where the current is high and the efficiency and power factor low). For voltages of e_5 and above, the motor starts and runs up to a speed near synchronism. For voltage e_4 three points exist, b_1, b_2, b_3, where the motor torque equals the load; b_1 and b_3 are stable, b_2 unstable. From below b_2 the motor slows down to b_3. From above b_2 it speeds up to b_1. The motor curve now has an un-

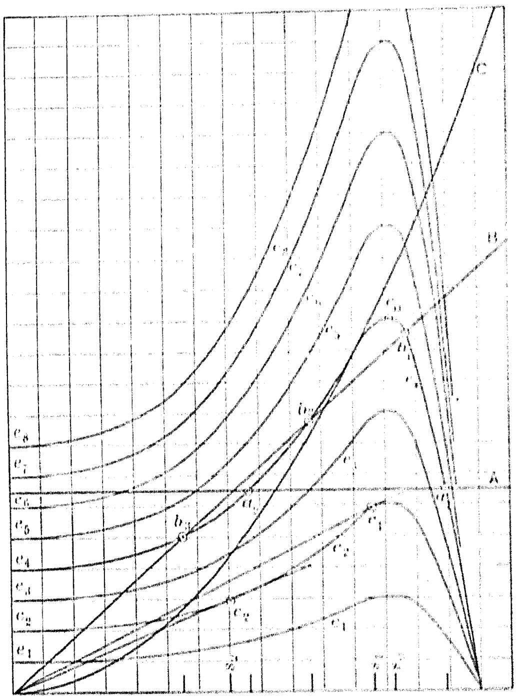

Fig. 1—Speed-Torque Curves of Induction Motor

stable branch between the speeds s_2 and s_1 (corresponding to the two points of contact, c_2 and c_1, of the motor torque with tangents from the origin, which for the sake of clearness have been illustrated on curve e_2), and two stable branches below s_2 and above s_1.

With a load requiring a torque proportional to the square of the speed, C, in Fig. 1 (fan, ship propeller), instability does not exist, but the conditions are always stable over the entire range

of the speed-torque curve of the motor, and the motor always starts and runs up to a definite speed, which is the only speed at which the motor can carry the particular load. With other shapes of motor torque curves—as those due to a drop of supply voltage with a decrease of speed—an unstable range may appear between two stable ranges, and in the case C also.

Probably the most important case of unstable electrical equilibrium is afforded by circuits containing an arc. It is the determining feature in the design of arc lamps, circuits and machinery, and is possibly responsible for more disturbances in electric circuits than any other phenomenon.

The voltage consumed by an arc decreases with increase of current, as shown by curve A, in Fig. 2. If then the arc is operated from a supply circuit of constant voltage, e_0, Fig. 2, and r is the resistance of this supply circuit outside of the arc, the voltage consumed by the resistance $r\,i$, is shown by B, in Fig. 2, and the total voltage of arc and resistance derived by adding A and B is given by C, in Fig. 2. As seen, two values of current exist, i_1 and i_2, at which the arc could operate in this circuit. The higher current i_1 is stable, the lower current i_2, is unstable, and the branch of the curve C below the minimum point i_0 is unstable; that above i_0 is stable.

On a constant-current circuit the arc at atmospheric pressure is stable.

Inversely, with the mercury arc in a vacuum, as the quartz lamp, instability may appear under certain conditions on a constant-current circuit, as the result of the relation of temperature and voltage. Increasing temperature increases the vapor pressure, and with it the voltage, and thus, on constant current, the power consumed by the vacuum arc. Increasing power consumption, however, increases the temperature, and thereby the voltage, and so on, and if the rate of temperature rise, due to increasing voltage, is greater than the rate of voltage rise due to increasing temperature, instability results, and the arc runs away; otherwise it is stable.

Similar phenomena, as shown by the arc, are exhibited by some solid conductors, which, in a certain temperature range, have a very high temperature coefficient; so-called "pyro-electrolytes". A typical volt-ampere curve of such a conductor is shown in Fig. 3. As seen, at voltage e_0 three values of current are possible, i_1, i_2, and i_3. Of these the low and the high ones are stable, the intermediate one i_2 unstable, and so is the entire

range between i_0 and i_0', the maximum and the minimum of the volt-ampere characteristic.

The Nernst lamp glower is such a pyro-electrolyte, and its operating current is on the unstable branch of the characteristic, therefore a steadying resistance or reactance is required, just as with an arc on constant voltage supply. Most of these conductors are chemical compounds, and at higher currents, and thus temperatures, their conduction becomes electrolytic.

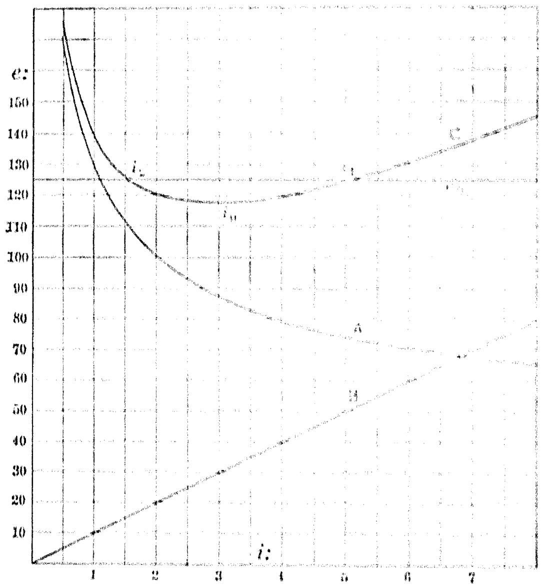

FIG. 2—VOLTAGE OF ARC

However, some elementary substances, as boron and silicon, also belong to this class of conductors.

(3) PERMANENT INSTABILITY

If the constants of an electric circuit, as resistance, inductance, capacity, disruptive strength, impressed voltage, etc., have values which cannot co-exist, the circuit is unstable, and remains so as long as these constants remain unchanged. Such instability usually leads to phenomena which are more or less periodic or intermittent.

The nature of these phenomena of permanent instability is

best shown by an example illustrated in Fig. 4. Let A and B be two conductors of an ungrounded high-potential transmission line, and $2e$ the voltage impressed between these two conductors. Let C represent the ground.

The capacity of the conductors A and B against ground may then be represented diagrammatically by two condensers $C_1 = C_2$, and the voltages from the lines to ground by e_1 and e_2. In general, the two line capacities are equal: $C_1 = C_2$, and the two voltages to ground thus equal also: $e_1 = e_2 = e$ with a single-phase, and $= \frac{2\,e}{\sqrt{3}}$ with a three-phase line.

Assume now that a ground P is brought near one of the lines A, but within the striking distance of the voltage e. A discharge

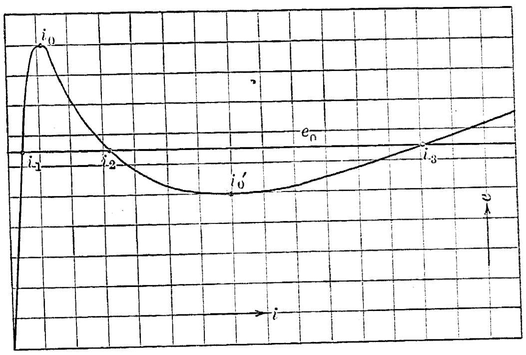

FIG. 3—VOLT-AMPERE CURVE OF "PYRO-ELECTROLYTE"

then occurs over the conductor P. Such may occur by the puncture of a line insulator, as is not infrequently the case. Let r = resistance of the discharge path P. While without this discharge path, the voltage between A and C would be $e_1 = e$ (assuming a single-phase circuit), with a grounded conductor P approaching line A within striking distance of voltage e, a discharge occurs over P, forming an arc, and the circuit of the impressed voltage $2e$ now comprises the condenser C_2 in series to the multiple circuit of condenser C_1 and arc P, and the condenser C_1 rapidly discharges, voltage e_1 decreases, and the voltage e_2 increases. With a decrease of voltage e_1, the discharge current i also decreases, and the voltage consumed by the discharge arc e' increases until the two voltages, e_1 and e', cross, as shown

in the curve diagram of Fig. 4. At this moment the current i in the arc vanishes, the arc ceases, and the shunt of the condenser C_1 formed by the discharge over P thus ceases. The voltage e_1 then rises, e_2 decreases, and the two voltages tend toward equality, $e_1 = e_2 = e$. Before this point is reached, however, the voltage e_1 has passed the disruptive strength of the discharge gap P, the discharge by the arc over P again starts, and the cycle thus repeats indefinitely.

In Fig. 4 are diagrammatically sketched voltage e_1 of condenser

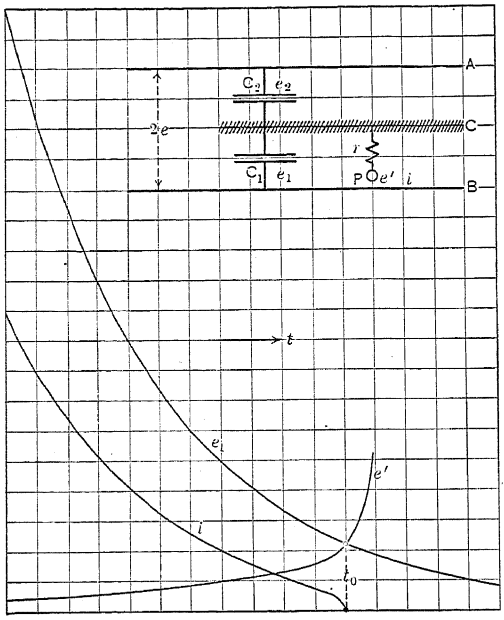

FIG. 4—ILLUSTRATING CONDITION OF PERMANENT INSTABILITY

C_1, the voltage e' consumed by the discharge arc over P, and the current i of this arc, under the assumption that r is sufficiently high to make the discharge non-oscillatory. If r is small each of these successive discharges is an oscillation.

Such an unstable circuit gives a continuous series of successive discharges, which are single impulses, as in Fig. 4, or more commonly are oscillations.

If the line conductors A and B in Fig. 4 have appreciable inductance, as is the case with transmission lines, in the charge

of the condenser C_1, after it has been discharged by the arc over P, the voltage e_1 would rise beyond e, approaching $2e$, and the discharge would thus start over P, even if the disruptive strength of this gap is higher than e, provided that it is still below the voltage momentarily reached by the oscillatory charge of the line condenser C_1.

This combination of two transmission line conductors and the ground conductor P, approaching near line A to a distance giving a striking voltage above e, but below the momentarily charging voltage of C_1, then constitutes a circuit which has two permanent conditions, one of stability and one of instability. If the voltage $2e$ is gradually applied, $e_1 = e_2 = e$, the condition is stable, as no discharge occurs over P. If, however, by some means, as a momentary overvoltage, a discharge is once produced over the spark gap P, the unstable condition of the circuit persists in the form of successive and recurrent discharges.

The most interesting class in this group of unstable electric systems is the oscillations resulting sometimes from a change of circuit conditions (switching, change of load, etc.) which continue indefinitely with constant intensity, or which steadily increase in intensity, and may thus be called permanent and cumulative surges, hunting, etc. They may be considered as transients in which the attenuation constant is zero or negative.

In the transient resulting from a change of circuit conditions, the energy which represents the difference of stored energy of the circuit before and after the change of circuit conditions, is dissipated by the energy loss in the circuit. As energy losses always occur, the intensity of a true transient thus must always be a maximum at the beginning, and steadily decrease to zero or to a permanent condition. An oscillation of constant intensity or of increasing intensity thus is possible only by an energy supply to the oscillating system brought about by the oscillation. If this energy supply is equal to the energy dissipation, constancy of the phenomenon results. If the energy supply is greater than the energy dissipation, the oscillation is cumulative, and steadily increases until self-destruction of the system results, or the increasing energy loss becomes equal to the energy supply, and a stationary condition of oscillation results. The mechanism of this energy supply to an oscillating system from a source of energy differing in frequency from that of the oscillation, is still practically unknown, and very little

investigating work has been done to clear up the phenomenon. It is not even generally understood that the phenomenon of a permanent or cumulative line surge involves an energy supply, or energy transformation, of a frequency equal to that of the oscillation.

Possibly the oldest and best known instance of such cumulative oscillations is the hunting of synchronous machines.

Cumulative oscillations between electromagnetic and electrostatic energy have been observed by their destructive effects in high-voltage electric circuits, on transformers and other apparatus, and have been, in a number of instances where their frequency was sufficiently low, recorded by the oscillograph. They obviously are the most dangerous phenomena in high-voltage electric circuits. Relatively little exact knowledge exists of their origin. Usually, if not always, an arc somewhere in the system is instrumental in the energy supply which maintains the oscillation. In some instances, as in wireless telegraphy, they have found industrial application. A systematic theoretical investigation of these cumulative electrical oscillations probably is one of the most important problems before the electrical engineer today.

The general nature of these permanent and cumulative oscillations and their origin by oscillating energy supply, from the transient of a change of circuit condition, is best illustrated by the instance of the hunting of synchronous machines, and this may, therefore, be investigated somewhat more in detail.

Practically all theoretical study of the hunting of synchronous machines has been limited to the calculation of the frequency of the transient oscillation of the synchronous machine, at a change of load, frequency or voltage, at synchronizing, etc. However, this transient oscillation is harmless, and becomes dangerous only if the oscillation ceases to be transient, but becomes permanent and cumulative; and thus the most important problem in the study of hunting is the determination of the cause which converts the transient oscillation into a cumulative one; that is, the determination of the source of the energy, and the mechanism of its transfer to the oscillating system. To design synchronous machines so as to have no or very little tendency to hunting, obviously requires a knowledge of those characteristics of design which are instrumental in the energy transfer to the oscillating system, and thereby cause hunting, so as to avoid them and produce the greatest possible inherent stability.

If, in an induction motor running loaded, at constant speed, the load is suddenly decreased, the torque of the motor being in excess of the reduced load causes an acceleration, and the speed increases. As, in an induction motor, the torque is a function of the speed, the increase of speed decreases the torque, and thereby decreases the increase of speed until that speed is reached at which the motor torque has dropped to equality with the load, and thereupon acceleration and further increase of speed ceases, and the motor continues in operation at the constant higher speed. That is, the induction motor reacts on a decrease of load by an increase of speed, which is gradual and steady without any oscillation.

If, on a synchronous motor running loaded, the load is suddenly decreased, the beginning of the phenomenon is the same as in the induction motor; the excess of motor torque causes an acceleration, that is, an increase of speed. However, in the synchronous motor the torque is not a function of the speed, but in a stable condition, the speed must always be the same, synchronism, and the torque is a function of the relative position of the rotor to the impressed frequency. The increase of speed, due to the excess torque resulting from the decreased load, causes the rotor to run ahead of its previous relative position, and thereby decreases the torque until by means of increased speed, the motor has run ahead from the relative position corresponding to the previous load, to the relative position corresponding to the decreased load. Then the acceleration, and with it the increase of speed, stops. But the speed is higher than in the beginning, that is, is above synchronism, and the rotor continues to run ahead, the torque continues to decrease, is now below that required by the load, and the latter thus exerts a retarding force, decreases the speed, and brings it back to synchronism. But when synchronous speed is reached again the rotor is ahead of its proper position, and thus cannot carry its load, and it begins to slow down, until it is brought back into its proper position. At this position, however, the speed is now below synchronism, and the rotor thus continues to drop back, and the motor torque increases beyond the load, thereby accelerates again to synchronous speed, etc., and in this manner conditions of synchronous speed, with the rotor position behind or ahead of the position corresponding to the load, alternate with conditions of proper relative position of the rotor, but below or above synchronous speed; that is, an oscil-

lation results which usually dies down at a rate depending on the energy losses resulting from the oscillation.

As seen, the characteristic of the synchronous machine is, that readjustment to a change of load requires a change of relative position of the rotor with regard to the impressed frequency without any change of speed, while a change of relative position can be accomplished only by a change of speed, and this results in an over-reaching in position and in speed; that is, in an oscillation.

Due to the energy losses caused by the oscillation, the successive swings decrease in amplitude, and the oscillation dies down. If, however, the torque which brings the rotor back from the position ahead or behind its normal position corresponding to the changed load (excess or deficiency of motor torque and of the torque required by the load) is greater than the torque which opposes the deviation of the rotor from its normal position, each swing tends to exceed the preceding one in amplitude, and if the energy losses are insufficient, the oscillation thus increases in amplitude and becomes cumulative; that is, hunting.

In Fig. 5 is shown diagrammatically, as p, the change of the relative position of the rotor, from p_1, corresponding to the previous load, to p_2, the position further forward corresponding to the decreased load: v then shows the oscillation of speed corresponding to the oscillation of position.

The dotted curve, w_1, then shows the energy losses resulting from the oscillation of speed (hysteresis and eddies in the pole faces, currents in damper windings), that is, the damping power, assumed as proportional to the square of the speed.

If there is no lag of the synchronizing force behind the position displacement, the synchronizing force, that is, the force which tends to bring the rotor back from a position behind or ahead of the position corresponding to the load, would be—or may approximately be assumed as—proportional to the position displacement p, but with reverse sign: positive or accelerating when p is negative or behind the normal position, negative or retarding when p is ahead. The synchronizing power, that is, the power exerted by the machine to return to the normal position, then is derived by multiplying $-p$ by v, and is shown dotted as w_2 in Fig. 5. As seen, it is a double-frequency alternation with zero as average.

The total resultant power or the resulting damping effect

which restored stability, then is the sum of the synchronizing power w_2 and the damping power w_1, and is shown by the dotted curve w. As seen, under the assumption of Fig. 5, in this case a rapid damping occurs.

If the damping winding, which consumes a part or all the power w_1, is inductive—and to a slight extent it always is—the current in the damping winding lags behind the e.m.f. induced in it by the oscillation, that is, lags behind the speed v, and the power w_1, or that part of it which is current times voltage, then ceases to be continuously negative or damping, but contains a

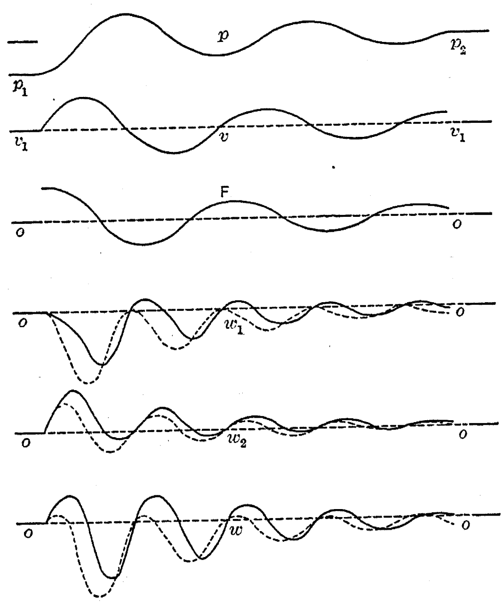

FIG. 5—OSCILLATIONS DUE TO CHANGE OF LOAD

positive period, and its average is greatly reduced, as shown by the drawn curve w_1, in Fig. 5; that is, inductivity of the damper winding is very harmful, and it is essential to design the damper winding as non-inductive as possible to give efficient damping.

With the change of position p, the current, and thus the armature reaction, and with it the magnetic flux of the machine, changes. A flux change cannot be brought about instantly, as it represents energy stored, and as a result the magnetic flux of the machine does not exactly correspond with the position p,

but lags behind it, and with it the synchronizing force F, as shown in Fig. 5, more or less, depending on the design of the machine.

The synchronizing power of the machine, $F v$, in the case of a lagging synchronizing force F, is shown by the drawn curve w_2. As seen, the positive ranges of the oscillation are greater than the negative ones; that is, the average of the oscillating synchronizing power is positive, supplying energy to the oscillating system, which energy tends to increase the amplitude of the oscillation; in other words, tends to produce cumulative hunting.

The total resulting power, $w = w_1 + w_2$, under these conditions, is shown by the drawn curve w, in Fig. 5. As seen, its average is still negative or energy consuming, that is, the oscillation still dies out, and stability is finally reached, but the average value of w in this case is so much less than in the case above discussed, that the dying out of the oscillation is much slower.

If now the damping power w_1 were still smaller, or the average synchronizing power w_2 greater, the average of w would become positive, supplying energy to the oscillating system. In other words, the oscillation would increase and hunting result. That is, if the average synchronizing power resulting from the lag of the synchronizing force behind the position exceeds the average damping power, hunting results. The condition of stability of the synchronous machine is, that the average damping power exceeds the average synchronizing power, and the more this is the case, the more stable is the machine; that is, the more rapidly the transient oscillation of readjustment to changed circuit conditions dies out.

Or, if

a = attenuation constant of the oscillating system,

$a < 0$ gives cumulative oscillation or hunting;

$a > 0$ gives stability.

Counting the time t from the moment of maximum backward position of the rotor, that is, the moment at which the load on the machine is decreased, and assuming sinusoidal variation, and denoting

$$\phi = 2 \pi f t = \omega t \tag{1}$$

where

$$f = \text{frequency of the oscillation,} \tag{2}$$

the relative position of the rotor may then be represented by

$$p = - p_0 \cdot \epsilon^{-a \phi} \cos \phi$$

where

$p_0 = p_2 - p_1 =$ position difference of

rotor resulting from change of load, (3)

$a =$ attenuation constant of oscillation. (4)

The velocity difference from that of uniform rotation then is

$$v = \frac{dp}{dt} = \omega \frac{dp}{d\phi} = \omega\, p_0\, \epsilon^{-a\phi} (\sin \phi + a \cos \phi) \quad (5)$$

Let

$$a = \tan \alpha; \quad 1 + a^2 = A^2 \quad (6)$$

hence

$$\sin \alpha = \frac{a}{A}; \quad \cos \alpha = \frac{1}{A} \quad (7)$$

it is

$$v = \omega\, p_0\, A\, \epsilon^{-a\phi} \sin (\phi + \alpha) \quad (8)$$

Let

$\gamma =$ lag of damping currents behind e. m. f. induced in damper windings; (9)

the damping power is

$$w_1 = - c\, v\, v_\gamma$$
$$= - c\, \omega^2\, p_0^2\, A^2\, \epsilon^{-2a\phi} \sin (\phi + \alpha) \sin (\phi + \alpha - \gamma) \quad (10)$$

where

$$c = \frac{w}{v^2} = \text{damping power per unit velocity} \quad (11)$$

Let

$\beta =$ lag of synchronizing force behind position displacement p, and (12)

$$\beta = \omega\, t_0 \quad (13)$$

where

$t_0 =$ time lag of synchronizing force. (14)

The synchronizing force then is

$$F = b\, p_0\, \epsilon^{-a\phi} \cos (\phi - \beta) \quad (15)$$

where

$b = \frac{F_0}{p_0}$ = ratio of synchronizing force to position displacement, or specific synchronizing force. **(16)**

The synchronizing power then is

$$w_2 = Fv = b\,\omega\,p_0^2\,A\,\epsilon^{-2a\phi}\sin(\phi+\alpha)\cos(\phi-\beta) \qquad \textbf{(17)}$$

The oscillating mechanical power is

$$w = \frac{d}{dt}\frac{mv^2}{2} = m\,\omega\,v\frac{dv}{d\phi}$$

$$= m\,\omega^3 p_0^2 A^2 \epsilon^{-2a\phi}\sin(\phi+\alpha)\{\cos(\phi+\alpha) - a\sin(\phi+\alpha)\} \qquad \textbf{(18)}$$

where

m = moving mass reduced to the radius, on which p is measured. **(19)**

It is, however,

$$w_1 + w_2 - w = 0. \qquad \textbf{(20)}$$

Hence, substituting (**10**), (**17**), (**18**) into (**20**) and cancelling,

$$b\cos(\phi-\beta) - c\,\omega\,A\sin(\phi+\alpha-\gamma) - m\,\omega^2 A\cos(\phi+\alpha) + m\,\omega^2 A\,a\sin(\phi+\alpha) = 0 \qquad \textbf{(21)}$$

This gives as the coefficients of $\cos\phi$ and $\sin\phi$ the equations

$$\left.\begin{array}{l} b\cos\beta - c\,\omega\,A\sin(\alpha-\gamma) - m\,\omega^2 A\cos\alpha + m\,\omega^2 A a\sin\alpha = 0 \\ b\sin\beta - c\,\omega\,A\cos(\alpha-\gamma) + m\,\omega^2 A\sin\alpha + m\,\omega^2 A a\cos\alpha = 0 \end{array}\right\} \qquad \textbf{(22)}$$

Substituting (**6**) and (**7**) and approximating from (**13**), for α as a small quantity,

$$\cos\beta = 1; \quad \sin\beta = \omega\,t_0 \qquad \textbf{(23)}$$

gives

$$\left.\begin{array}{ll} b - c\,\omega\,(a\cos\gamma - \sin\gamma) - m\,\omega^2(1-a^2) & = 0 \\ bt_0 - c\,(\cos\gamma + a\sin\gamma) + 2m\,\omega\,a & = 0 \end{array}\right\} \qquad \textbf{(24)}$$

This gives the values, neglecting smaller quantities,

$$a = \frac{c\cos\gamma - b\,t_0}{\sqrt{4\,mb - c^2\cos 2\gamma + b^2 t_0^2}} \qquad \textbf{(25)}$$

$$\omega = \frac{1}{2\,m}\{\sqrt{4\,mb - c^2\cos 2\gamma + b^2 t_0^2} + c\sin\gamma\} \qquad \textbf{(26)}$$

$$f = \frac{\omega}{2\pi} \qquad \textbf{(27)}$$

These equations (**25**) and (**26**) apply only for small values of a, but become inaccurate for larger values of a, that is, very rapid damping. However, the latter case is of lesser importance.

$$a = 0 \text{ gives}$$
$$b\,t_0 = c \cos \gamma$$

Hence

$$\left.\begin{aligned} c &> \frac{b\,t_0}{\cos \gamma} \\ \text{or} \quad t_0 &> \frac{c \cos \gamma}{b} \end{aligned}\right\} \qquad (\mathbf{28})$$

is the condition of stability of the synchronous machine.

If

$$t_0 = 0$$
$$\gamma = 0$$

then

$$a = \frac{c}{\sqrt{4\,mb - c^2}}$$

$$\omega = \frac{\sqrt{4\,mb - c^2}}{2m}$$

and, if, also,

$$c = 0$$

$$\omega = \sqrt{\frac{b}{m}}$$

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DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

BY ALFRED E. WALLER

Dynamo lighting equipments on motor cars are required to maintain at all times a supply of electric energy sufficient for proper road lighting. It is therefore natural, in the design of such apparatus, to decide first what may be accepted as a satisfactory set of lamps for motor car use. When this point has been determined, the capacity of dynamo, battery, and auxiliary apparatus may be readily deduced.

The choice of lamps is influenced by a great many considerations, and among these is the variable element of individual preference. Some drivers prefer to have a good deal of light near the car, others insist upon lamps which will project the light a considerable distance ahead, and leave objects close at hand in comparative darkness. Many arguments are offered in favor of each type, and, in order to have his product meet with general favor, a lamp designer must take both extremes into account.

A great deal of interesting experimental work has been done with headlights of both American and foreign design, in order to determine the characteristics of the most suitable lamp and reflector.

As a result the 21-c.p. six-volt tungsten lamp has been adopted for use with a parabolic reflector measuring 10 in. (25.4 cm.) across the opening.

This choice was governed by several considerations. In the first place it was shown that with lamps of this description a road 50 ft. (15.2 m.) wide could be perfectly lighted for a distance of at least 1000 ft. (304.8 m.) in advance of the car. Objects on the road could be distinguished practically as far away as

would be possible in daylight, and always in ample time to stop or turn aside as the case rendered necessary.

In the second place, 10-in. (25.4 cm.) reflectors were used because they did not necessitate extremely large headlights, which, beside being costly, would detract from the appearance of a motor car. The importance of having lamps properly focused was brought out in these experiments. For the best results the lamp filament must be located exactly at the focus of the parabolic reflector, and the reflector should be so designed that the focus is well back from the opening. A comparatively deep reflector makes the angle of the direct rays not intercepted by it, rather small, consequently a greater proportion of the total candle power may be projected in a useful direction. The effect is particularly good when the lights are placed at least three ft. (0.9 m.) from the ground. At this height the shadows caused by slight ridges and undulations in the road are not so apparent as when the lights are placed lower.

The 10-in. (2.54 cm.) parabolic reflector adopted, measures about 5½ in. (14 cm.) in depth. This reflector has a focus of 1⅛ in. (2.85 cm.) and, when properly focused, a 21-c.p. lamp gives ample light on the road near the car and at the same time has very good distance qualities.

Very deep reflectors both of the eight-in. (20.3 cm.) and 10-in. (25.4 cm.) diameter sizes were tried, but it was found that these did not give satisfactory lighting near the car.

Twenty-four c.p. lamps were tried out in the 10-in. (25.4 cm.) reflector, but the difference in illumination was scarcely noticeable, and was more than offset by the fact that the 24-c.p. lamps required 14 per cent more current than the 21-c.p.

The side and rear lights, which are used only as signal lights, and have little value for road lighting purposes, were equipped with four-c.p. and two-c.p. lamps respectively. Lights of lower candle power than this would have been ample for the purpose, but in the smaller sizes of lamps the filaments were found to be too frail to give reliable service under the conditions of severe vibration encountered on a motor car.

Considering, therefore, that a proper equipment consists of a pair of 21-c.p. headlights, a pair of four-c.p. side lights, and a two-c.p. rear light, we find the current taken by these lamps to be seven amperes, 1.7 amperes and 0.6 amperes respectively, making a total load of 9.3 amperes at 6 volts. In addition to this equipment we find on the average car an electric horn and

a speedometer light, but as these devices are used only intermittently, their current is not an important factor in determining the maximum dynamo capacity which will be required.

Allowing for the intermittent use of the speedometer light and electric horn, it is evident from the figures quoted above, that an adequate lighting dynamo must have an output of 10 amperes, in order to maintain at all times a sufficient supply of energy. Further, as the dynamo is available as a source of energy only when the motor car engine is running, a battery must be provided to furnish current when the engine is at rest. A three-cell lead battery has been universally adopted for use with 6-volt lights, and the dynamo must therefore be capable of furnishing 10 amperes at a voltage sufficient to charge a battery of this type.

Our next consideration is the car speed at which the full load output of the dynamo must be delivered. Much of the mileage covered by the average motorist is traversed at a speed of not more than 18 miles per hour, and if we are to reserve the storage battery for use when the motor car engine is not running, our dynamo must be so geared that it will carry the entire light load when the car is traveling at this speed or above. If the speed falls below say 18 miles per hour, more or less current will be drawn from the battery, as the dynamo will not be generating its full capacity. A great deal of night driving at slow speed with all lights on, would in time run down the storage battery, but it is found in practise that little slow-speed running is done with all lights on. In the city, where this condition does prevail to a large extent, the headlights are not as a rule in use, and the load taken by the remainder of the equipment is readily supplied by the dynamo. Further, if the car is used in the day time at all, the charge accumulated by this running serves to keep the battery always charged and in perfect condition. If cars are left standing, the headlights are of course turned off and the 2.3 ampere load represented by the side and rear lights may be carried for some time upon a proper battery.

The ideal electric lighting system is entirely automatic. Means must be provided for connecting the dynamo to the battery when speed proper for charging has been reached, and for disconnecting the dynamo from the battery when the speed is reduced to a point where a reversal of current is about to take place. This is a feature which is present in all properly designed lighting systems.

In some systems now on the market, the connecting and disconnecting from the battery is accomplished by a centrifugally operated switch. The dynamo speed which corresponds to a correct voltage for charging is predetermined, and the centrifugal device is set to close the circuit at this time, and to open it as soon as the speed is reduced below the safe point. In most cases, however, the operation is accomplished by means of an electromagnetic switch. This switch or relay, as commonly constructed, has two windings, one of high resistance which is permanently connected across the armature terminals. The relay is set so that it closes the circuit between the dynamo and the battery, when energized by a potential sufficient for charging the battery, and opens the circuit when the dynamo voltage is reduced below this point. As a precautionary measure, a series winding is placed upon the relay with the shunt winding. This series winding reenforces the shunt winding while charging is going on, but bucks it upon reversal of current, thus tending to produce complete demagnetization of the relay.

One of the most important functions of the automatic lighting system is the control of the dynamo output at the very high speeds reached by motor car engines. It will be readily understood that if a dynamo is arranged so that it is driven at say 1000 rev. per min. at a car speed of 20 miles (32 km.) per hour, and is delivering its full output at this speed, when the car speed has been increased to 40 miles (64.3 km.) or even 60 miles (96.5 km.) per hour, a dynamo not properly protected will be forced to generate current far in excess of its rated capacity and a burn-out will inevitably result. No matter what type of dynamo is used, there must be some means of compensating for the current fluctuations which occur with speed changes.

As in the case of the automatic switch for connecting to the battery, the more difficult problem of controlling dynamo output has been accomplished by means of both mechanical and electrical devices. It is my intention in this paper merely to describe a number of regulators which are now widely used, without commenting either favorably or unfavorably upon their respective merits.

Considering first the mechanical types of control, we have slipping clutches of different designs. For example, one manufacturer uses a clutch composed of two members, one of which is rigidly attached to the dynamo shaft, and the other to some convenient drive shaft. The clutch members are held together

by spring pressure, and, as the speed of the driving member increases, this spring pressure is neutralized by means of centrifugal governors, which oppose the spring tension, and allow slippage between the clutch members, the amount of slippage depending upon the speed of the driving member. This allows the dynamo to be driven at a substantially constant speed, regardless of that of the motor car.

The regulator adopted by another manufacturer has in it a centrifugal governor which turns at the same speed as the dynamo, and moves a small contact arm over a number of steps of resistance inserted in the field circuit of the dynamo. The greater the dynamo speed, the more resistance is inserted with the field, so that a substantially constant output is obtained.

There is a much larger number of electrical devices for this purpose. One of the earliest consisted of a resistance made of small carbon disks arranged in a tube and connected in series with the dynamo field winding. The disks are normally pressed very tightly together by a spring, and in this condition have a low electrical resistance. The device is so arranged that the armature current of the dynamo passes through a series coil, which is arranged to pull directly against the spring which compresses the carbon disks. Consequently when excessive charging rates are reached, the pull of the series coil tends to neutralize the spring pressure upon the carbon disks, and the resistance of the field circuit is increased by the release of pressure.

One method which is much used with the permanent field type of dynamo is to design a machine with high armature reactions, and to depend upon these to prevent excessive generation of current. Compound windings have been successfully used with both bipolar and multipolar dynamos for this work, in spite of the very great range of speed encountered.

Other manufacturers have used double field windings, one portion arranged to opppose the flux generated by the other portion. These opposing or bucking coils are thrown into play at the proper moment by a series relay inserted in the armature circuit.

One magneto type dynamo manufactured has a permanent field with auxiliary electromagnetic field windings, which are disconnected when a certain current has been reached. If the speed is increased beyond this point, the auxiliary electromagnetic fields are again brought into play and are energized so as to oppose the flux of the permanent field. This gives a very wide range of regulation.

In several cases, modifications of the controls described above have been used by regulating the dynamo for a certain maximum voltage instead of maximum current.

In another lighting system, regulation is accomplished by the introduction of a coil of iron wire in the armature circuit. This coil has the property of increasing resistance very slowly, until a certain critical current is reached, and then increasing at a very rapid rate to several times its original resistance. The terminals of a bucking field coil are connected across this series coil of iron wire, which is so designed that the critical point where its resistance increases rapidly, is reached when the maximum dynamo current is being generated. Normally the potential difference applied to the terminals of the bucking coil is negligible, but when the iron wire has become sufficiently heated, this potential difference becomes sufficient to generate a considerable flux in the bucking coil, and to reduce materially the output of the dynamo.

Among the devices designed to secure constant dynamo output at varying speeds, are several foreign inventions. In one of these a bipolar shunt-wound dynamo is arranged with a pair of auxiliary poles placed between the main poles of the machine. The auxiliary poles are not wound, but are excited by the cross magnetization caused by the working current in the dynamo armature. Two brushes are placed in the neutral position relative to the main poles, and are sufficiently wide to short-circuit several armature coils during the period of commutation. When the armature is revolved the dynamo behaves as any ordinary shunt-wound machine, except that the load current in the armature conductors, by virtue of its cross-magnetizing ampere-turns, sets up a flux in the auxiliary unwound poles, provided to receive it. The armature coils short-circuited by the brushes cut this cross flux and consequently have a short-circuit current induced in them, which is proportional to the cross flux and to the speed of rotation. This short-circuit current acts in such a direction as to demagnetize the main wound poles. In this manner the voltage of the dynamo is regulated so as to compensate for speed changes and also for load changes.

One foreign manufacturer has designed a distributing panel, in which each circuit on the car has a properly proportioned coil of resistance wire in series with it. This wire is of such gage and length that it permits a certain amount of current

to flow in the circuit, this being predetermined, and increases in resistance to eight or ten times its nominal value when this current value is exceeded, thus protecting the lamps against burn-out.

In a well-known French design a bipolar dynamo is used, with two windings on each pole, the pairs being wound to produce magnetization in the same direction. One side of each of the four coils is connected to the negative brush of the dynamo, and the four remaining terminals are connected to the positive brush, through four small breakers arranged concentrically around the dynamo shaft. These breakers are opened in succession by a cam on the end of the dynamo shaft, and only one breaker is opened at a time. At low speeds the effect produced by opening momentarily one of the four field coils and closing it again before opening another, is negligible, but as the speed is increased the interruptions become so rapid that the dynamo field does not have time to build up to its full intensity, and constant output may be secured from the dynamo over a wide speed range.

In the particular lighting system under consideration a plain shunt-wound dynamo was adopted as being the simplest and most reliable type, and a system of control was developed which gives perfectly satisfactory regulation. The necessary regulation is secured by means of a single step of resistance inserted in series with the dynamo field. This resistance, which is of such a value that it will limit the dynamo output to its predetermined maximum at the highest car speed obtainable, is normally short-circuited, but the short circuit is removed from the resistance when the maximum charging current has been reached. This is accomplished by means of a relay, only one winding of which carries the armature current. In practise, the short circuit is removed from the resistance in series with the dynamo field when a current of 10.1 amperes has been reached, and when this resistance is thus inserted in the field circuit, the dynamo output immediately falls off. When the current is reduced to 9.9 amperes, the resistance is once more short-circuited, and, as the interval of time required for this change in current is very short, an extremely rapid vibration of the relay contact is set up, and a substantially constant current is obtained over a wide range of speed.

In the early experimenting, a relay of the familiar telegraph type was used, but lengthy experiments led to the adoption

of a modified type in which the trunnions or pivots are replaced by a flexible phosphor-bronze hinge of suitable gage and width. This construction is found to be highly satisfactory, and is not affected by vibration.

There are a number of other systems of control which are quite as efficient and well known as these I have mentioned, and a great deal of time might be devoted to their discussion and comparison. It is necessary at this time, however, to consider the initial speed at which a dynamo should be designed to give its full output. This is an important consideration, and is so closely related to the construction of the motor car engine with which the system is to be used, that the general arrangement of the engine must be carefully taken into account.

It is well known that the size, weight and cost of a dynamo of any particular type, depends not only upon the watt output, but also upon the speed at which this output is delivered. Consider as an example the shunt-wound dynamo; one which will deliver 7.5 volts and 10 amperes at 1500 rev. per min., costs 30 per cent less than one which will deliver the same output at 1000 rev. per min., and less than half as much as one designed for a speed of 500 rev. per min. The weights of the respective machines are in approximately the same ratio as their cost.

A shunt-wound dynamo designed for the stated output at approximately 1000 rev. per min. weighs about 21 lb. (9.5 kg.) and can be made approximately 8 in. (20.3 cm.) long by $5\frac{3}{8}$ in. (13.2 cm.) high by $4\frac{3}{4}$ in. (12 cm.) wide. If it is required to secure the same output at 500 rev. per min. the weight must be increased to approximately 35 lb. (15.8 kg.) and the dimensions become $9\frac{1}{4}$ in. (23.5 cm.) by $7\frac{1}{2}$ in. (18 cm.) by $4\frac{3}{4}$ in. (12 cm.) approximately. On the average four-cylinder motor car, a 1000-revolution dynamo is run at about twice engine speed for the best results, and the 500-revolution dynamo should be run at engine speed.

Bearing these facts in mind, the selection of a dynamo for any particular automobile engine becomes a matter of judgment and must be largely governed by the structure and arrangement of the engine itself. Speaking broadly, it will be found that when a 500-rev. per min. dynamo may be readily coupled to a shaft which runs at engine speed, its extra weight and cost are justified by the fact that it renders sprockets and chain or gears, and their care, unnecessary. On motors where an installation of this type entails the extension of a shaft

not readily accessible, or the use of a countershaft or an idler gear or some other device for bringing the direct drive into a convenient location, a chain-driven dynamo geared to run at twice engine speed may be used to advantage.

Where a geared dynamo is necessary, the shunt-wound machine designed to deliver its output at 1000 rev. per min. and driven at approximately twice engine speed, appears to be the most advantageous design in weight, cost and size. Such a dynamo when driven at twice engine speed on a car with 36-in. (0.9 m.) rear wheels, geared 3½ to 1 on the back axle, will start charging the battery at from six to seven miles (9.6 to 11.2 km.) per hour, and will deliver its full output of 10 amperes at about 15 miles (24.1 km.) per hour. The same dynamo on a car geared 3 to 1 with 36 in. (0.9 m.) rear wheels, would begin to charge the battery at approximately 9 miles (14.4 km.) per hour, and will balance the lamp load at approximately 18 miles (28.9 km.) per hour. A machine of this type has distinct points of advantage over a dynamo designed to deliver its output at either a higher or a lower speed.

Considering first a higher speed dynamo, let us assume a rated speed of 1500 rev. per min. for full output. This dynamo is smaller, lighter and cheaper than a dynamo designed for 1000 rev. per min., but must be driven at approximately three times engine speed. In practise if a ⅜-in. (9.5 mm.) pitch silent chain is used, the driven and driving sprockets will have 15 and 45 teeth respectively. This means a chain speed of 2250 ft. (685.8 m.) per minute at 45 miles (72.4 km.) per hour of the car and 3000 ft. (914.4 m.) per minute at 60 miles (96.5 km.) per hour. These speeds are too high for best results and cause rapid wear of the chain. It should be noted also that the chain is likely to become noisy when driven at this speed.

On the other hand, a dynamo driven at less than twice engine speed, in order to secure lower chain speed, and less wear on the bearings, is not an advantageous arrangement. The cost and weight of the dynamo are immediately increased, without the elimination of sprockets.

It becomes evident, therefore, that if the chain speed reached by the drive of the 1000-rev. per min. dynamo is not excessive, it has a decided advantage over either of the types just mentioned. Investigation shows that in practise, sprockets of 30 and 15 teeth would be used with ⅜-in. (9.5 mm.) pitch silent chain, and at 45 miles (72.4 km.) per hour the chain speed would

be 1500 ft. (457.2 m.) per minute, and at 60 miles (96.5 km.) per hour it would run 2000 ft. (609.6 m.) per minute. These speeds are not excessive and are within the limits of the speed at which a chain may be used with best efficiency.

The problem of driving dynamos on different types of motor car engines is capable of many solutions. In some cases it is possible to secure a direct drive at engine speed, through an Oldham coupling, and this is an instance in which the low-speed dynamo may be used to great advantage. In many cases it is possible to extend the pump shaft back through the pump casing, and to obtain a direct connection in this manner. In other instances it has been possible to move the magneto and to install in the place formerly occupied by it a dynamo with a double-end shaft, to which the magneto is afterwards connected by means of an Oldham coupling, and the two units driven in tandem fashion. This arrangement on a six-cylinder car requires a dynamo wound to deliver its output at 1½ times engine speed, that is, about 750 rev. per min.

With the 1000-rev. per min. dynamo, drive may be secured by means of a sprocket installed on the pump or magneto shaft, a sprocket on an extended half-time shaft, or one fastened to the crank shaft directly back of the clutch which engages the starting handle. In other installations it is possible to drive by a gear, meshing with one of the timing gears, or with one of those in the transmission. Either of these last methods make a very satisfactory installation where they can be used, as the gears, encased and running in oil, are almost absolutely noiseless.

All of these methods and numerous others have been tried out and shown to be entirely satisfactory, both as regards noiseless operation and life.

The remaining points to be considered are the size and capacity of battery to be used, and the method of wiring.

In order to meet satisfactorily the severe conditions to which it is apt to be subjected, the battery must have plates sufficiently large to stand charging at the maximum dynamo output for an indefinite time, without deterioration. This condition would be imposed upon it by an automobile owner who drives only in the day time. It should have sufficient capacity to maintain all lights on the car for six hours, and to carry the side and rear lights only, for from 20 to 24 hours, without receiving any charge.

Exhaustive experiments have demonstrated that a battery with 160 sq. in. (852.3 sq. cm.) or more of positive plate surface

and 100 sq. in. (645.2 sq. cm.) of negative plate surface, is capable of standing a 10-ampere charging rate for very long periods, even when no current is taken from it. It is unquestionably possible to damage a battery of the above size by charging at a 10-ampere rate, if carried on indefinitely on a test bench. The condition of motor car service, however, tend to offset the main causes of deterioration which become noticeable when the batteries are charged at high rates. In the first place a battery charged continuously at a high rate becomes overheated, and this heat softens the plates to such an extent that they are readily disintegrated. Another cause of decay is the formation of large bubbles of gas on the negative plates, which, when they finally break away from the plates, take with them particles of active material, especially when this has become softened due to heating.

The chance of overheating a battery due to continuous high charging rates, becomes rather small when we consider that it is seldom, in practise, that a battery is charged continuously at the maximum rate for more than a few hours at a time. It is seldom indeed that a dynamo in motor car service delivers its full output for several hours at a time without intermission, because automobiles are rarely driven at a continuous speed of 18 miles (28.9 km.) per hour or above for long intervals. In addition to the frequent slowing down of the motor car engine, due to coasting down hill, or turning corners, there are often periods when it is not running or is running slowly, so that the dynamo does not generate its maximum current. It has been proved in practise that in the average installation no appreciable heating takes place, and that even the drivers who maintain the highest average speed never raise their batteries to an excessive temperature. Referring to the second cause for deterioration, it will be evident that the vibration always present in motor car service, makes it practically impossible to form large bubbles upon the battery plates. The jolting of the automobile becomes practically a substitute for the mechanical agitator which is used in many large stationary battery plants.

A battery installed on the average motor car is operating under ideal conditions, as it is either charging or discharging nearly all the time. If the plate surface mentioned above is used, the 9½-ampere load represented by the total light equipment may be carried for approximately 3¼ hours, while the side and rear lights may be kept bright for at least 24 hours. It will be ap-

parent that the $3\frac{1}{4}$-hour limit for the length of time during which the battery will take care of the entire load, is hardly long enough, so that a battery used in a motor car equipment should have approximately double the capacity given, or approximately 80 ampere-hours. In a very large number of lighting systems now operating successfully, standard makes of batteries rated at 80 ampere-hours with a 10-ampere discharge rate, are proving entirely adequate. A battery of this type has considerably more than the necessary plate area to stand the 10-ampere charging rate indefinitely, and will carry all lamps for at least six hours, a longer time than would be ordinarily required.

The remaining point now to be considered is the method of wiring, and type of wire used. In many of the first lighting systems, the proposition of a ground return for all fixtures was pointed out, but in practically all instances the system of running two wires to each lamp and fixture has been adopted. Ground returns in many cases brought about ignition complications, and the system of two wires has a decided advantage in that one conductor may be grounded accidentally without interfering with the lights. On the ground return system an abrasion or injury to the current-carrying wire is apt to put the entire system out of operation. In a recommendation to a special advisory committee of the Society of Automobile Engineers, Mr. Leonard Kebler, a member of the Society, proposed that for motor car installation, a cable be used capable of standing a test of 12 hours immersion in oil, 12 hours immersion in gasolene, and 12 hours immersion in water, and then stand 500 volts applied between the two conductors without a breakdown. Wire of this type has been used extensively by several manufacturers and has been found to give excellent results.

The insulation of wire for motor car use, should be composed preferably of some material which is not affected by oil or gasolene, and is not softened by ordinary temperatures. Where rubber is used it should be protected against oil and gasolene to prevent the possibility of grounds and short circuits.

In concluding, it may be said of the lighting system wiring that the manufacturer should, if possible, cut all wires to length and make all connections before shipment. Experience proves that the highest satisfaction with motor car lighting equipments may be obtained only when the wiring is done by skilled operators. Consequently, a lighting system designed

in such a manner that it may be purchased for any particular make or model of car, with all wires cut to length and fitted with proper plugs, all connections made to panels, switches, etc., possesses distinct advantages. The work of installation is reduced practically to fastening the switch, controlling panel, battery, and dynamo to the car. It has been found possible to arrange lighting systems in such a manner that the only connections which need to be made by the user, are those between the system of wiring and the dynamo, and also to the battery terminals.

By arranging the dynamo connections with different sizes of binding posts, so that the wires cannot be put on in wrong order, and treating the battery binding posts in the same manner, the chances of trouble due to improper wiring are reduced to a minimum, and satisfaction is secured from the point of view both of the manufacturer and the automobile owner.

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, November 14, 1913.

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

BY ALEXANDER CHURCHWARD

For supplying current for starting and lighting the modern motor car a constant-speed dynamo has many advantages over every other type of dynamo, viz:

1. It charges a battery as it should be charged; that is, with a comparatively large current when the battery is low and empty, tapering off to a small charging rate when the battery is full and at the gassing point.
2. Its comparatively low speed, even at high car speed, means long life, small wear and maintenance, and—what is most necessary—reliability.
3. Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by a "bucking series" coil or by regulation of the field current.

In other words, the loss due to the friction and slipping of the clutch is less than the core loss of variable speed machines running at high speeds.

4. Its ability to run the lights, even when the battery is disconnected—accidentally or otherwise.
5. It can be geared to cut in at very low car speeds, as the speed of the dynamo armature never exceeds a safe, predetermined limit.

Experience has shown in the past four years that it is far better to charge a battery at a moderate rate whenever the car attains a speed of 8 miles (12.8 km.) per hour than to charge at a very low rate at 10 miles (16 km.) per hour and gradually increase the charging rate as the car speed rises. A variable-speed,

constant-current dynamo, giving enough current to take care of the lights, invariably over-charges the battery on long daylight runs of some hours' duration. The user may not have to renew the battery frequently, but the direct effect is to boil the solution out of the battery, and at some time when current is

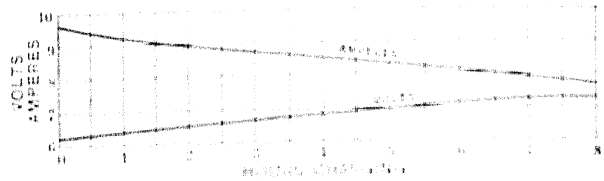

FIG. 1—TAPER CHARGE EFFECT OF CONSTANT SPEED DYNAMO.

needed the battery fails because of a lack of electrolyte; or whatever electrolyte is left is so concentrated as to injure the plates.

This is not the case with a constant-speed machine, which gives neither constant current nor constant potential. When the

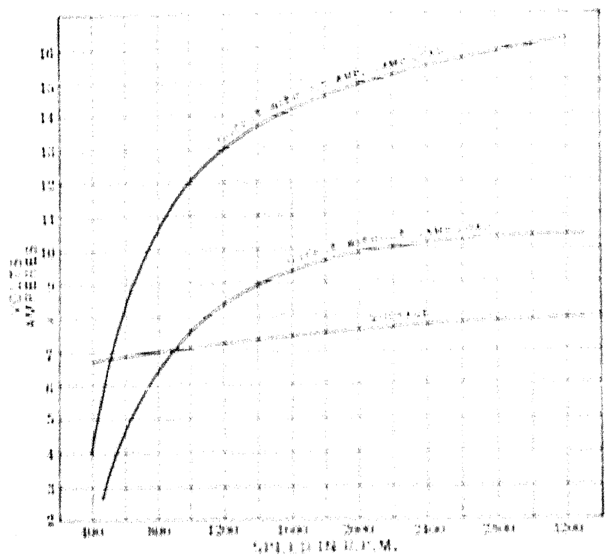

FIG. 2—OVERCHARGING EFFECT OF VARIABLE-SPEED DYNAMO.

battery is low it will give a comparatively heavy current, say 10 amperes, which will taper off to four or five amperes as the battery becomes fully charged, the voltage rising from approximately 6.5 volts to 7.75 volts when battery of three cells is fully charged. Fig. 1 shows the tapering charge effect, while Fig. 2

shows the over-charge effect of a variable-speed machine; the battery voltage rising to over eight volts, from which of course the lamps and battery would both suffer.

The constant-speed machine can be compounded so that when lamps are turned on it will maintain a constant potential of a proper value at the lamps.

The advantages of the compound-wound, constant-speed dynamo, that is compound-wound for lighting and shunt-wound

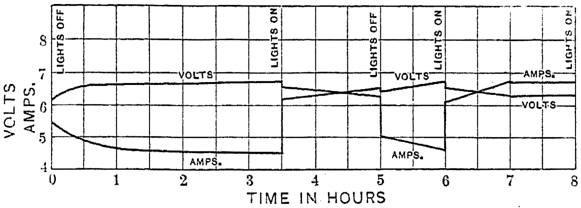

FIG. 3—TAPER CHARGE AND COMPOUND CHARACTERISTICS OF DYNAMO

for charging battery, must be at once apparent to even the most casual observer:

1. Proper rate of charging, dependent upon condition of battery.

2. Tapering charge as battery is filled up.

3. Sufficient current to light the lamps and to put a small charge into the battery. Take for example a system equipped with lamps that call for a total of eight amperes at six volts:

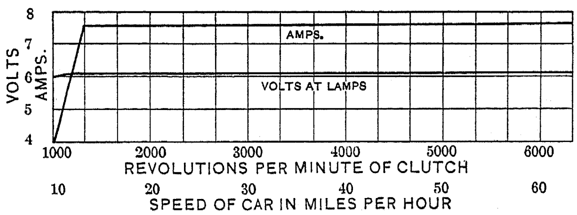

FIG. 4—VOLTAGE AT LAMPS AT DIFFERENT SPEEDS.

The charging rate to the battery will vary from 10 amperes when the battery is cold and low to five amperes when the battery is warm and charged.

If we now turn on the lamps, which are connected through the series or compound winding, the machine will give nine amperes, the battery receiving at first one ampere, while its counter electromotive force is high from just coming off charge; but it will gradually settle until the dynamo is giving 10 amperes,

eight of which go to the lights and two to the battery. This will keep the battery voltage at approximately 6.6 volts. There will be a drop in the wiring, instruments, etc., of from 0.4 to 0.5 of a volt, so that the voltage at the six-volt lamps will be main-

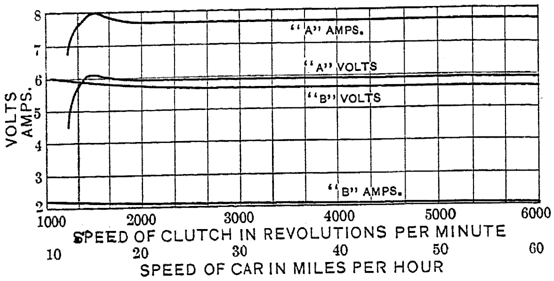

FIG. 5—VOLTAGE AT LAMPS WITH VARYING SPEEDS; BATTERY DISCONNECTED.

tained within 0.1 of a volt. Figs. 3, 4 and 5 show how the potential is maintained at the lamps.

Mention has been made, above, only of a lamp potential of six volts, corresponding to three cells of lead battery, as we have

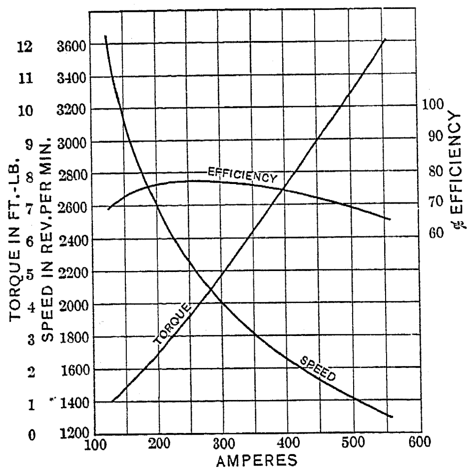

FIG. 6—CHARACTERISTICS OF SIX-VOLT SERIES-WOUND STARTING MOTORS.

found that it is possible to design our starting system so that we have a more efficient motor at six volts—the standard voltage for ignition—than most of the other systems using 18 to 24 volts.

Experience in designing electric automobile motors during the past 15 years has demonstrated that to get the most out of a battery, regardless of the number of cells, the best design which can be employed is a series motor with a steep torque characteristic (see Fig. 6).

A shunt-wound dynamo at constant speed being the best for charging batteries, and having characteristics exactly opposite to those of a series motor, explains the reason for our adopting the two-unit electrical system for starting and lighting. For the same generator output and the same power delivered as a motor, a single unit cannot be built any lighter or cheaper than a two-unit system.

It is unnecessary to point out why the two-unit electrical sytem is more reliable than a single-unit system, as one unit can fail without crippling the car.

In regard to weight of different voltage systems, the single unit system almost always calls for a larger number of cells in series for starting, and in multiple for lighting. The battery capacity is invariably fixed by the lighting conditions, and not by the starting conditions; and the amount of power required for starting is very small compared with that required for lighting. In fact, it is only a surface discharge. For instance: Take a six-volt battery of 80-ampere-hour capacity, that is, eight amperes for 10 hours. It will require 11 plates per cell, five positive and six negative, or 15 positive and 18 negative total; and compare it with a battery for 24-volt starting system using four sets of batteries in parallel for lighting, each cell consisting of two positive plates and three negative, or a total of 24 positive and 36 negative, let alone extra jars, acid, connectors, etc., which will increase the weight approximately 20 per cent above that of the six-volt battery of the same capacity.

Take another example of a 12-volt starting, and 12-volt, three-wire lighting system: The same battery capacity will be needed, only in this case 40 ampere-hours at 12 volts; therefore, there will be three extra positive and six extra negative plates, or one per cell; also extra acid, extra connectors, etc.; and the increase of weight will be approximately 10 per cent, or as much as the weight of the generator unit itself.

Therefore, the writer maintains that a six-volt double unit system properly designed and built will weigh less and be more efficient per pound than any system designed for a higher voltage.

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, November 14, 1913.

ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

BY FRANK CONRAD

The principal electrical devices used on the gasoline automobile perform the functions of ignition, lighting and engine starting, their relative importance being in the order given. The service of the first two elements is of a continuous nature; that of the third is intermittent and momentary. The success of the gasoline motor is intimately connected with the success of the ignition system, a condition which has resulted in the development of this device to a high degree of perfection.

The ignition device in its simplest terms consists of a source of electrical supply, an induction coil for producing a high-voltage discharge from an insulated to a grounded electrode in the firing chamber, and a control device or timer for making and breaking the primary circuit of the induction coil. The conditions which have to be met by this ignition system comprises an unfailing source of electrical energy, an igniting spark at all operating speeds and accurate timing of this spark. The dry batteries used in the earlier systems were found to be unreliable. This caused attention to be turned to some form of generator, and due to its greater simplicity and greater range of operating speed, the permanent magnet type, or magneto, was found to be the most suitable. This apparatus possesses several inherent features which are desirable in a spark-producing device. Thus the voltage induced in its windings is approximately proportional to the speed. This tends to maintain a constant spark at all speeds, as the duration of current flow in the primary circuit will be inversely proportional to the speed of the ignition device.

With the advent of electric lighting, a generator of different

characteristics from that of the ignition machine was required. As light is required during periods when the generator is not operating, the use of a storage battery is entailed, and as the generator must operate in parallel with this battery over a wide range of speed, its terminal voltage must be nearly constant over this range. For this reason, and in view of the previous high development of the magneto, it was at first found most convenient to install a separate generator for the lighting system, the ignition thus being operated from a generator having a voltage characteristic approximately proportional to the speed and the lighting system from a generator having a voltage characteristic independent of the speed within its working limits.

As a step towards simplification, it would seem desirable to modify the electric equipment so that a single generator could be used, for furnishing power both to the ignition apparatus and the lighting system. It is of course evident that this generator would require to be of the constant voltage type, as it is necessary that it operate in conjunction with a storage battery. This involves the redesign of the ignition system so that it will operate from a constant potential supply. The earlier form of ignition device, consisting of an induction coil having a vibrating contactor and controlled by a timing device driven synchronously with the engine, met this condition, but it embodied several defects that it was possible to correct in the magneto ignition device. In a simple induction coil device, the contact is made at a predetermined point on the travel of the engine crank shaft, and after the elapsed time required for the current to build up in the primary of the induction coil, it is broken by the magnetically operated vibrator. This vibrator continues to make and break the primary circuit as long as the contact on the engine-driven timer remain closed. The result is a series of sparks in the engine cylinder at each firing period. Due to the fixed time period between the make of the circuit by the timer and the spark in the cylinder, there will be a corresponding lag of this spark as the speed of the engine is increased, thus requiring adjustment of the timer for the particular speed at which the engine is operated in order to obtain efficient results.

To obviate this, the time of break in the primary of the ignition system should be mechanically determined by the rotation of the engine, thereby avoiding the lag inherent in the magnetically operated breaker.

In the magneto device, this condition is met, as no magnetic-

ally operated contactor is used, the primary circuit being opened and closed mechanically by the rotating element. Therefore, there will be no lag of the spark as the speed of the engine is increased. This, however, implies that the duration of current flow in the primary circuit will be correspondingly shorter at the higher speeds. However, as the magneto generates a correspondingly higher voltage, the result will be an increased rate of building up of primary current which will compensate for this shorter time, thus maintaining a constant volume of spark. Unfortunately, in actual practise, this condition will be somewhat overdone, thus at the low operating speeds, the voltage generated will be insufficient to produce normal current flow, owing to the resistance and losses in the device, and, at the very high speeds, the voltage will have increased to such a value that the resistance losses will have a very slight effect, so that the secondary induced current will reach its highest value.

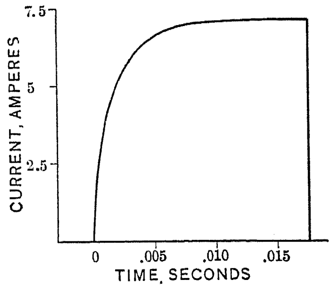

FIG. 1—PRIMARY COIL CURRENT.

In the case of the ignition device operated from a constant-potential circuit and having a fixed angular time of contact, the opposite result will be obtained; that is, at the very low operating speeds, the current in the primary circuit will build up to a value determined only by the resistance of the circuit, while at the very high engine speeds, sufficient time may not have elapsed for the current to build up to a value necessary to obtain a satisfactory spark. It is therefore necessary to introduce some opposing feature which will limit the current at the lower speeds, and still permit of sufficient flow at the higher speeds. A device in which this has been accomplished will have advantages over the magneto, in that it will have no minimum operating speed, and, in addition, at the higher operating speeds, the secondary current will not be of sufficient value to burn away the spark plug electrodes unnecessarily.

The oscillograms show the current wave shape of the primary and secondary circuits of an induction coil used with such a system. Fig. 1 is the primary current, in which contact has been made for a sufficient time to allow the current to build up to its maximum value, which is approximately eight amperes. With

this coil a primary current of about five amperes is required to give a satisfactory discharge in the secondary circuit, and from the oscillograms it can be seen that about 0.003 second is required for current to build up to this value.

In the case of the four-cylinder engine in which the ignition device is driven at engine speed, this would require an arc of contact at 200 revolutions per minute of 3.6 deg., and at 2000 revolutions per minute, 36 deg.

Fig. 2 is an oscillogram of the current in the secondary circuit of this coil. Fig. 3 shows an oscillogram of the secondary circuit of a well-known magneto ignition device. A comparison of the two oscillograms would indicate that the magneto would produce a very much hotter spark than in the case of the constant potential device. Analysis, however, will show that

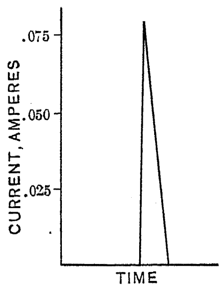

FIG. 2—SECONDARY COIL CURRENT.

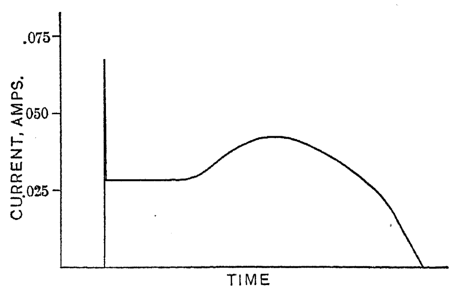

FIG. 3—MAGNETO SECONDARY—FULL ADVANCE

the initial current flow of the two devices is practically the same, the difference being that, in the case of the magneto, this flow is maintained for a considerable period, the maintenance of the current being brought about by the construction of the magneto, in that the primary and secondary windings are wound directly on the revolving armature, the secondary winding therefore cutting the magnetic field by the revolution of the armature, the same as the primary circuit. When due to the interruption of the primary circuit, an induced voltage is set up in the secondary circuit; the current flow across the spark plug electrodes, which is started by this high voltage, will be maintained by the voltage induced by the rotation of the secondary winding in the magnetic field. This continued current flow, however, has no practical advantages, as the explosive gases, which directly surround, and are in range of, the sparking points, are

burned in a period of time probably not exceeding 0.001 second. A continued maintenance of the arc would therefore be of no further value, and would only cause the spark plug electrodes to be needlessly burned away.

An interrupter mechanism for controlling the flow of primary current, and which has been designed in line with the conditions outlined above, is shown in Fig. 4. In this device the angular time of contact is varied with the speed within working limits, so that the primary current will, at all speeds, build up to approximately the same value, thus producing a constant spark in the explosion chamber.

This action is brought about by two centrifugal operating cams which change their position with change in speed so that the contact device is held closed for an approximately constant time. This cam device not only performs the function of maintaining a constant angular time contact, but also advances the time of break with increase of speed to allow for the average time required for the combustible mixture in the cylinder to explode. This, in the magneto device, is accomplished by manual adjustment for the different speeds.

It is not possible to eliminate entirely the manual control, as there are other conditions than that of speed which determine the proper firing point, such as the quality of the explosive mixture and the temperature of the engine cylinders. This adjustment, however, is not required for each change in speed, but rather for the general conditions under which the engine is operating, so that only occasional attention to this control will be required. By the use of this variable contact device, it is possible to operate the coil at its most efficient point, thus obtaining a good spark throughout the working range of speed and with a minimum current consumption.

An advantage of an ignition system of this type is that it is possible to mount it directly on the lighting generator so that it forms part of the same, thus obviating the additional drive which is required in the case of a separate ignition system and, furthermore, it has the advantage over the magneto type, in that it has no minimum operating speed, a spark being produced no matter how slowly the engine is being turned over, thus lending itself particularly to applications in which an electric motor is used to turn over the engine for starting purposes.

As it is desirable that the combined generator and ignition device be installed on the same mounting and drive furnished

for the usual magneto, the generator should be so designed that it will have the proper range of operating speed. For a four-cylinder arrangement this is equivalent to the engine speed, and, on a six-cylinder engine, to one and a half times engine speed. It has been found in practise that it is desirable to have the generator capable of delivering an amount of current equivalent to the average lamp load when the car is being operated at a speed of 15 miles (24 km.) per hour. With the average gear ratio and size of wheels, this would be approximately 500 rev. per min. of the generator, the maximum running speed would be in the neighborhood of 2000 rev. per min. This would give a working range of speed of from 500 to 2000 rev. per min. on the four-cylinder, and 750 to 3000 on the six-cylinder engine.

The illustration, Fig. 5, shows a completed device of this type suitable for a 6-cylinder engine. The induction coil is mounted directly in the high-tension distributor, so that there are no high-tension connections except the leads to the spark plugs on the cylinders. It, therefore, in all respects, will be equivalent to a high-tension magneto of the self-contained type, and has advantages of a constant spark at all speeds, thus giving very good operation at low engine speed, and of furnishing power for lights and charging storage batteries. The regulation of the generator is obtained by means of a demagnetizing series coil in the circuit of the battery, thus maintaining constant charging current. The lighting circuit is so connected that the current supplied directly to the lamps will not pass through the series coil. This tends to maintain a constant charging current independent of the lamp load, and allows of this charging current being adjusted for a minimum value. The curve, Fig. 6, shows the output of this generator at varying speeds, with and without a lamp load of nine amperes.

For starting the gasoline engine, a motor is used which draws power from the storage battery. There are two general schemes possible, namely, the use of the lighting generator as a motor, and the use of a separate motor. The power required for turning over the average engine, at the speeds commonly employed, will range from one-half to one horse power. It is therefore evident that, if the lighting generator should be used as a starting motor, and at its normal operating speed, it would require an extremely heavy machine. In order to reduce this weight, a special driving arrangement might be furnished which would allow the generator to operate at engine speed when

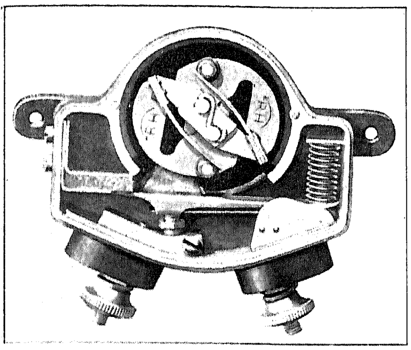

Fig. 4 [CONRAD]

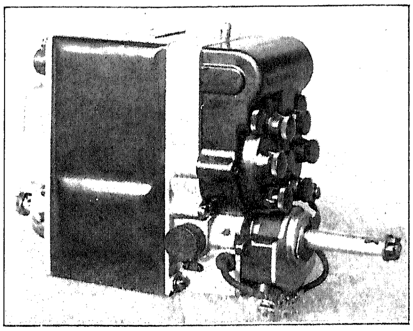

Fig. 5 [CONRAD]

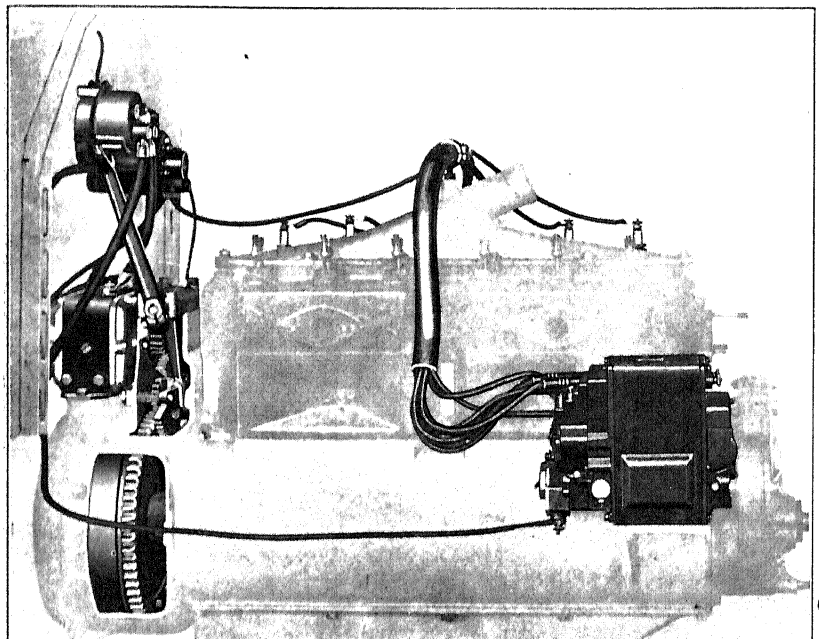

Fig. 9 [CONRAD]

being driven as a generator, and allow a considerable speed reduction from this generator to the engine when being operated as a motor. This implies a low-speed generator and a high-speed motor, which, for efficient design, necessitates double windings and commutators. Due to the general complication of this arrangement, the scheme of using a separate starting motor is to be preferred. This motor can have its proportions best worked out for its operation as a motor, and without the use of any inactive material, which would be necessary in the case of a combination machine. In order to reduce its weight to the lowest possible amount, it should be

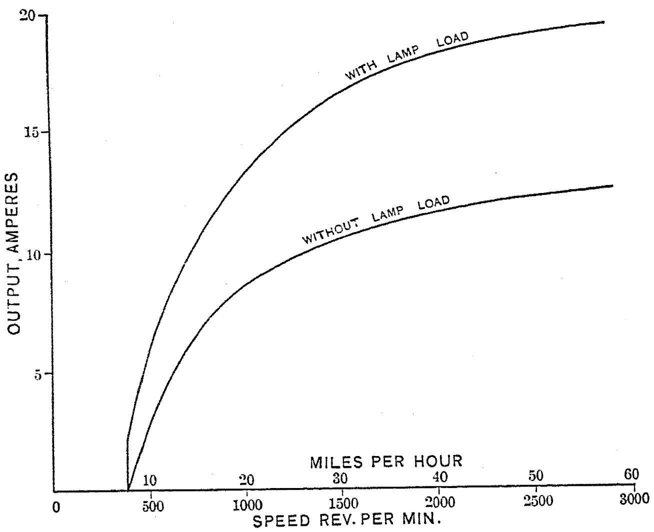

FIG. 6

operated at the highest speed consistent with the use of an efficient gearing between the motor and engine, the normal operating speed, in actual practise, being between the limits of 1000 and 2500 rev. per min., the higher speeds being used where weight is the paramount consideration, and the lower speeds being used where it is necessary that a very quiet drive be obtained.

From the point of view of the design of the motor, there are no particular characteristics required other than those obtained with a series motor. The efficiency should be as high as is consistent with light weight, and the locked torque should be as

great as possible, in order to minimize the possibility of failure to start when the engine is cold and stiff.

In the gearing between the motor and engine, there are certain conditions which must be met, due to the peculiarity of the load which the motor is driving. It is necessary to introduce some device which will prevent the gasoline engine from driving the motor, as, due to the comparatively high gear ratio, the motor will be operating at an excessive speed at even a comparatively low operating speed of the gasoline engine. This device consists of what is known as an over-running clutch. The torque also varies considerably during each revolution of the engine, due to the compression and expansion of the gases in the cylinders, this variation, of course, being much greater in a four- than in a six-cylinder engine. The curve, Fig. 7, shows the relative torques required by a four-cylinder engine under two conditions, namely, that of low temperature involving high friction losses due to cold oil in the bearings, and under the

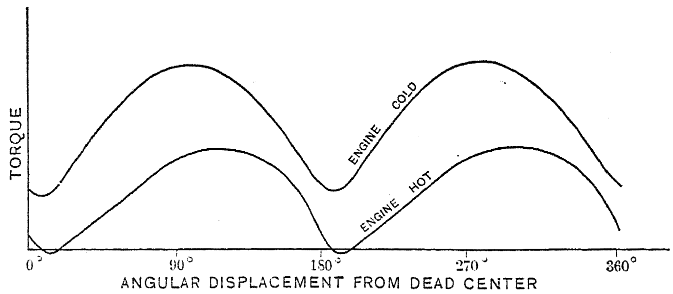

FIG. 7—TURN-OVER TORQUE OF FOUR-CYLINDER ENGINE.

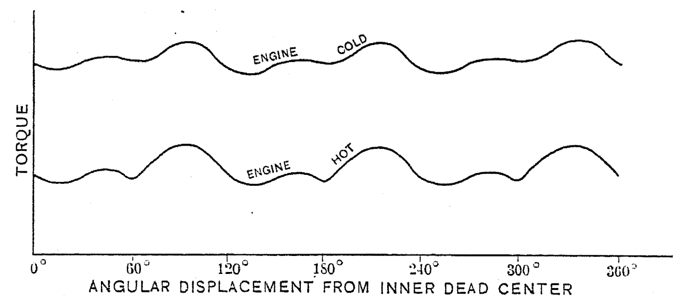

FIG. 8—TURN-OVER TORQUE OF SIX-CYLINDER ENGINE.

condition of high temperature, which greatly reduces the friction. The curve, Fig. 8, shows the torque required by a six-cylinder engine under the same conditions.

It will be seen that in the case of the hot four-cylinder engine, the torque required to drive it during certain parts of a revolution is negative, the engine thus tending to drive the starting motor. In order to secure a quiet drive, it is essential that, in the disconnecting devices used between motor and engine, there be no appreciable back-lash or lost motion in the over-running clutch device. The effect of this, however, can be minimized by reducing the inertia of the starting motor armature so that it can more closely follow the speed of the gasoline engine over the period of negative torque. The effect also decreases with increase of cranking speed.

As the service of the starting devices is of a momentary nature, it is customary to so proportion the design that the apparatus is worked under conditions of excessive overload, as compared to continuously operated devices. This is particularly true as regards the storage battery, the usual discharge rates being somewhere in the neighborhood of the 20-minute rate. In order to reduce to a minimum the internal drop under this excessive rate, a much thinner plate is used than is the case with batteries intended to be operated only under normal rating. The continuous capacity of the motor should be such that it can completely discharge a fully charged battery under any conditions without injury.

Fig. 9 shows a complete installation on an automobile engine of a set of units as described above. In this application, the starting motor is mounted on the top of the flywheel casing and drives the engine through a gear cut in the periphery of this flywheel, a push button projecting through the dash serving to operate the control switch and shift a sliding pinion into mesh with the flywheel gear.

Where the starting motor is connected to the engine through the medium of a chain drive there is no sliding gear used, but the sprocket wheel on the engine shaft drives through the medium of an over-running clutch. This allows the starting motor to drive the engine, but permits of free running of the engine, independent of the starting motor. The control device consists of a simple switch in the starting motor circuit.

DISCUSSION ON "DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS" (WALLER), "ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS" (CHURCHWARD), AND "ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES" (CONRAD), NEW YORK, N. Y., NOVEMBER 14, 1913.

H. Ward Leonard: I should like to put before the meeting what I think are a few of the desirable features we should strive to reach in an automatic lighting system for charging a storage battery and operating the lights upon a motor car, and I think the same conditions, so far as the automatic lighting and charging are concerned, may apply equally well to the case of train lighting. These are very broad generalities that I shall specify and while, in each case, they may have been already realized in some one of the various systems, I am not sure that there is upon the market at the moment any one system that contains them all. The points to which I refer are as follows:

1. The automatic regulator shall so control the dynamo output that under all working conditions, including accidental short circuit, the dynamo current shall not exceed its normal full-load rated current.

2. The automatic control shall be such that current will be forced through the battery even if its resistance be abnormally high due to bad sulphating of the plates caused by neglect, the object being to insure the automatic removal of all sulphate, thereby restoring the battery to good working condition.

3. All movable elements of automatic regulating devices shall act independently of dash pots, liquids, frictional driving devices, pivots, oil, grease, graphite, centrifugal devices, and shall be substantially independent of the effects of gravity, and shocks of the road.

4. The automatic regulator shall not have any part subject to wear and therefore requiring adjustment by the operator.

5. The automatic regulator shall be unaffected by any changes of temperature met with in practise, and the dynamo current shall be independent of the changes of temperature to which its windings are subjected in practise.

6. The racing of the engine shall not materially increase the current produced by the dynamo even momentarily, the object being to avoid subjecting the lamps to excessive voltage with consequent blackening and possible instantaneous burnout.

7. As soon as the battery is so fully charged as to be gassing strongly, the current shall be automatically reduced to prevent the driving off of the water of the battery solution.

8. There shall be provided in plain sight of the operator an automatic indicator, which shall continually and positively indicate whether the battery is fully charged or not, and whether

the battery is being charged or discharged, and the value of the current into or from the battery.

9. In case the battery be broken or inoperative for any reason, it shall be possible for the lamps to be operated by the dynamo alone, under ordinary operating conditions.

My experience in this line dates back to the time when, in 1888, I put on the first train lighting system in this country, which operated between Chicago and Milwaukee, and I learned at that time, or thought I did, that the chief problem in a case of this character is to maintain the battery in perfect condition, in a condition ready to perform its duty at all times; and this seems to be equivalent to saying that the battery must be kept absolutely free from sulphate and able to deliver its full capacity. I think that is the case in the lighting and storage system in automobiles where there is such a strong demand made upon the battery relative to the area of the plates. It is necessary to keep that battery in perfect condition all the time if we are going to avoid failures in the future. My opinion of the matter is that this boils down to the statement that the whole problem really hangs upon the design of the controller of the dynamo.

Leonard Kebler: In reading over the paper by Mr. Churchward, I notice a statement which differs from my previous ideas upon this subject.

Mr. Churchward, speaking of the constant-speed dynamo, says: "Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by a bucking series coil, or by regulation of the field current."

This statement is quite contradictory to the theory which I have always held in regard to this matter, and I therefore have had some tests made to check this up.

The theory pertaining to this is that when a motor armature is driven at a constant speed and generates a constant current under any one condition of the battery, with a constant field, then the torque necessary to drive this armature must be constant. The driver of a slipping-clutch-controlled armature varies in speed, but, as stated above, the torque remains constant. The power of the driver is the product of the torque times the speed, so in this case the power will vary directly as the speed.

In practise the clutch begins to slip at a speed of approximately 14 miles (22.5 km.) an hour, and at higher speeds the amperes remain practically constant under any one circuit condition. My theory is that at 42 miles (67.5 km.) per hour the dynamo will require at least three times the power that it does at 14 miles (22.5 km.), although the output remains constant.

The results of my tests indicate that this theory is correct. This additional power necessary at higher speeds is represented by the heat generated by the friction clutch, and by the addi-

tional power necessary to drive the fan which is used to cool this clutch.

This friction of the slipping clutch necessarily entails a certain amount of wear, consequently a periodic readjustment of the clutch is necessary. Otherwise, the ampere charging rate will become gradually lower until the operator's attention is forcibly called to the low rate by the fact that the battery is not sufficiently charged.

Mr. Waller described a system which employs a shunt-wound dynamo having a vibrating arm in the field circuit, this arm being actuated by the armature current, to rapidly insert and cut out a resistance in series with the field, so as to keep automatically a constant armature current. I know from tests made in the past that such a system takes practically the same power to drive at all speeds above say 14 miles per hour, so I assumed that it was more efficient than the one of which Mr. Churchward says, "Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by ....regulation of the field current."

The tests made were as follows: A variable-speed electric motor, the speed variation being obtained by inserting resistance in series with the field, was run idle at various speeds in order to find the power necessary to run it idle at these speeds. It was then direct-connected to one of the dynamos equipped with a slipping clutch control, and was run at varying speeds with both the dynamo armature circuit and the field circuit open, in order that we might find the increased power necessary to overcome the friction losses, fan loss, etc., of the dynamo. The same tests were then made with one of the shunt-wound dynamos employing vibratory control in the shunt field circuit, described by Mr. Waller. Then separate runs were made with each of these two dynamos, the dynamo in each case being connected to a three-cell storage battery and the controller arranged in each case to deliver approximately 8 amperes. The results of these tests are shown graphically in Fig. 1.

The tests show that at about 2450 rev. per min. the motor driving the dynamo with the slipping clutch required $2\frac{1}{4}$ times as much power to drive as it did to drive the shunt-wound machine with the vibrating controller. In each case the amperes generated were about 8.

It should be remembered that this includes the loss in the electric driving motor, and if we deduct the amount of power necessary to drive the driving motor idle at 2450 rev. per min. from the amount of power required when the slipping clutch type machine and the shunt-wound machine respectively were being driven by it, we find that the additional power necessary to drive the slipping clutch machine is practically 3.8 times that necessary to drive the shunt-wound machine with the vibrating regulator.

It is common practise to drive the driving member of the

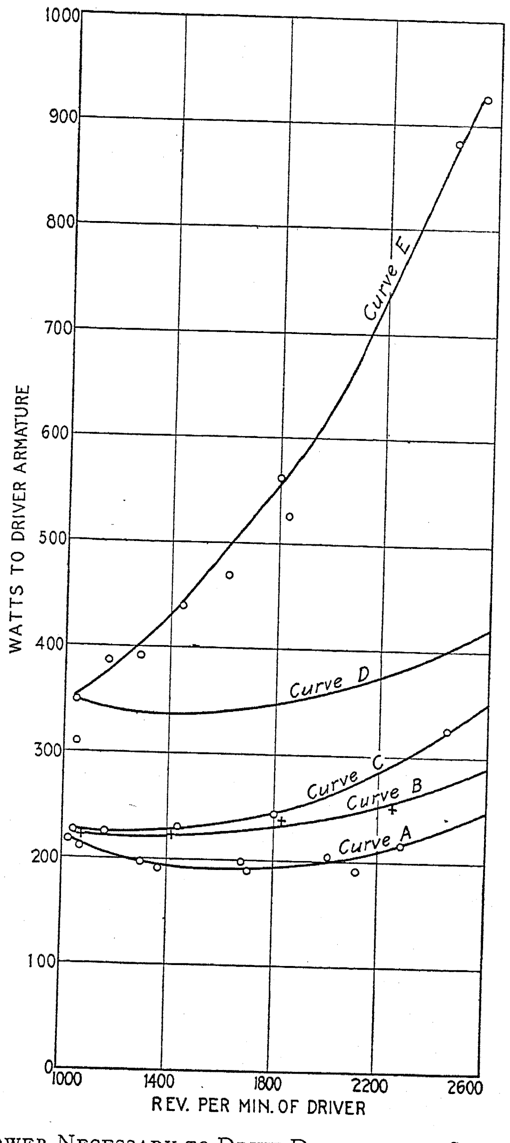

FIG. 1—POWER NECESSARY TO DRIVE DYNAMO WITH SLIPPING CLUTCH CONTROL, AND DYNAMO WITH VIBRATORY FIELD CONTROL, AT VARIOUS SPEEDS.

Curve A—Power taken by driving motor, running idle.
Curve B—Motor driving dynamo with vibratory control, all circuits open.
Curve C—Motor driving dynamo with slipping clutch control, all circuits open
Curve D—Motor driving dynamo with vibratory control, charging three-cell battery at rates varying from 8.2 to 9 amperes.
Curve E—Motor driving dynamo with slipping clutch control, charging three-cell battery at rates varying from 6.5 to 8.5 amperes.

slipping clutch dynamo in question at 2.7 times engine speed. With this drive a speed of 2450 is the equivalent of about 30 miles (48.2 km.) per hour of the average motor car, geared $3\frac{1}{4}$ to 1 at the back axle with 36-in. (91-cm.) wheels. When geared in this way the slipping clutch dynamo will give its full output, and the clutch will begin to slip at about 13 or 14 miles (21 or 22.5 km.) an hour. It will be noticed that at 30 miles (48.2 km.) per hour the slipping clutch dynamo takes about 330 per cent more power to drive it than it does at 13 miles (21 km.) per hour. Under the same circumstances the power necessary to drive the shunt-wound dynamo with the vibrating regulator is only 25 per cent greater at the added speed.

Almon W. Copley: Mr. Churchward's arguments for the use of a clutch type generator for automobile lighting are in several instances open to question. In his second reason he states that

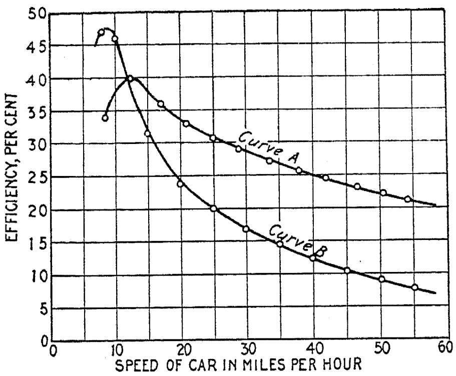

FIG. 2—TEST OF AUTOMOBILE LIGHTING GENERATORS, CHARGING BATTERY ONLY

Curve A—Bucking series coil type
Curve B—Slipping clutch type

the low speed of the armature even at high engine speeds insures long life and reliability. It seems to me that he is overlooking a very important part of the apparatus when he confines himself to the armature. It is true that this type of generator has a low armature speed, but one member of the clutch must revolve at very much greater speed, and moreover, it must be driven at this speed by gearing or chain drive from the engine. Mr. Churchward's curves show that this part must run at about $2\frac{1}{2}$ times engine speed and the problem of driving at this speed is a very serious one. Will not the bearings of this part of the machine wear much more than those of the armature of an engine-speed bucking series coil type generator, or one driven at $1\frac{1}{2}$ times engine speed? The question of the wearing of the chain or gears and the quietness of the drive must also be considered.

But the most objectionable feature of the clutch type machine is

the clutch itself. It can hardly be supposed that this clutch, slipping as it does practically continuously, can stay in proper adjustment and can have either the long life or the reliability of a machine not using this device. When the engine is running at 1500 rev. per min., *i.e.*, 40 miles (64 km.) per hour car speed, one clutch member is revolving at 3750 rev. per min. and the other at 1200 rev. per min., and with this slipping of 2550 rev. per min. there is transmitted energy to drive the armature and charge the battery at 8 or 10 amperes, it can easily be seen that there will be a great amount of heat generated at the slipping surface and consequent heavy wear and shortened life of the parts.

This also shows the weakness of the fifth argument advanced by Mr. Churchward for the use of this type of machine.

The answer to the third argument, *i.e.*, the comparative efficiency of slipping clutch type and bucking series coil type ma-

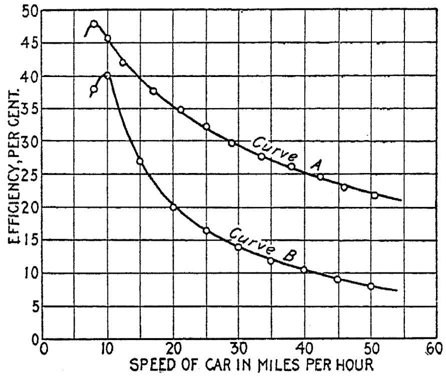

FIG. 3—TEST OF AUTOMOBILE LIGHTING GENERATORS, WITH BATTERY AND 8-AMPERE LAMP LOAD

Curve A—Bucking series coil type
Curve B—Slipping clutch type

chines, is also suggested by what I have said. If there is a large amount of heat generated at the clutch, the efficiency of a machine incorporating it must be low. Tests just completed on the latest designs of the best-known make of each of these two types of machine demonstrate this. The curves in Figs. 2 and 3 show the results of the test. Fig. 2 gives the efficiences of the two machines at varying speeds while carrying only the battery charging current (the lamp load disconnected). Fig. 3 gives the efficiency with an 8-ampere lamp load connected. It seems to me that these show clearly the falsity of Mr. Churchward's theory. The efficiency of the "bucking series coil" type is lower than that of the "slipping clutch" type only at very low car speeds with lights off, and at medium and high car speeds, or at all speeds when the lights are on, the former is very much higher than the latter. The dropping off of the efficiency of the

bucking series coil type at high speed is not such as to indicate extreme core loss under this condition as Mr. Churchward implies.

By reference to the curves the amount of energy absorbed by the clutch can be figured. It is fair to assume that the losses in the armature of the machine are the same at all clutch speeds above 1200 rev. per min., as the armature runs no faster than this. At 1200 rev. per min. the efficiency as shown in Fig. 2 is 40 per cent. The energy supplied the battery is 66 watts. This makes the losses in the armature 99 watts. Now at 50 miles (80.5 km.) per hour (5000 rev. per min.) the energy supplied the battery is the same and the armature loss is the same, totaling 165 watts, while the total energy required to drive the machine is 800 watts. This means that 635 watts are absorbed by the clutch (almost a horse power). The clutch cannot absorb this energy without getting excessively hot and certainly cannot stand this condition without rapid deterioration.

I wish also to point out that the slipping clutch type of machine is not well adapted for the application of ignition parts to it. The best type of machine for this purpose is one driven at engine speed for four-cylinder engines or $1\frac{1}{2}$ times engine speed for six-cylinder. The combination of the two functions in one machine is highly desirable, as it is economical to keep the number of units on the engine a minimum, provided combinations can be made which do not sacrifice anything as regards the performance, life or reliability of any of the individual parts.

Both Mr. Churchward and Mr. Conrad have pointed out the desirability of keeping the starting motor and the generator in separate units, on account of the inherent characteristics of the machines being so different. Mr. Conrad has shown a combined lighting and ignition generator, however, which sacrifices nothing in either the generator or the ignition system. The use of this machine with a starting motor makes necessary only two units; on many of the small engines it is necessary to limit the electrical equipment to this number of units on account of lack of room for more. On the larger engines, also, it is desirable, as it secures the neat, clean appearance of the engine so much sought for by engine and car builders.

I would also take exception to the statement Mr. Waller makes in regard to the merits of the double-wire and single-wire systems of wiring. It should be remembered that almost invariably one side of the battery is grounded—this being done on account of the ignition, which is always of the single-wire system. There is no question as to either the current-carrying capacity or conductivity of the car frame. Therefore, the use of two wires simply introduces an unnecessary complication and a higher resistance return path for the current than the car frame.

With the single-wire system the wire can be better insulated and still take up much less room than the two wires of a double-wire system. The problem of the insulation of the sockets,

lamps, and other fixtures is much simpler with the single-wire system, as more room is available for this purpose. In any electrical circuit of moderate voltage, whether for railway work, lighting or power work, the single-wire system would invariably be used were it not for the problem of obtaining a good ground return on account of such complications as electrolysis, difference of earth potential, etc. None of these complications is met in the automobile frame and there is no reason at all for complicating an inherently simple system by making it two-wire. Single-wire systems are now used quite extensively for car wiring and have demonstrated their practicability and simplicity.

A. D. T. Libby: When the chairman made the statement that the starting and lighting systems were getting down to a point where it was a question of the survival of the fittest, he hit the nail on the head. I believe the whole trend of automobile lighting and starting is fast coming to that point. In the early days, before they had magneto ignition, they started out with four cells of dry battery, giving six volts. Finally some one who had some trouble with his dry cells put on storage batteries equivalent to his dry cells, and they have stuck right along at six volts. The whole trend of engineering, from a power and electric light man's standpoint, is the other way, upward, instead of downward.

There is a mean to all things. If you adopt the 24-volt system, then you must have a controller with a large number of multiple contacts to throw the batteries from series, used in the starting, over to multiple, for the lighting, and the complications involved in this kind of a system are altogether too great for operating in an automobile. I am strongly in favor of, and have always advocated the 12-volt system. It gives the advantages of a higher voltage system without the disadvantages due to complications in the wiring, switches, controllers, etc., and it gives a system which is as simple as the six-volt system, without the many disadvantages thereof. There is no question but that a 12-volt starting motor has more "kick" in it than a six-volt machine. With six volts your brushes are subjected to more or less dust and dirt and you are troubled with these contacts which the low potential will not go through as readily as the 12 volts. I think the final survivor in the starting and lighting work will be the 12-volt system.

The question has been brought up of the single-wire system of lighting cars. There are a number of car makers who are turning out a large number of cars this year with single-contact lamps. I think this kind of a system is wrong. If there is a ground on any one wire of your system, the whole thing is put out of action, while with the 12-volt, two-or three-wire system, or even with the six-volt metallic system, without any ground, if you should happen to get a ground on one wire it will not trouble you at all; in that case you have two chances instead of one. I believe that the single-wire contact systems now being put out will give more or less trouble in the future. They may

not give any trouble while the car is new, and the wiring is in good order, but when the parts begin to get out of order the trouble will start.

The last speaker raised the point that in the one-wire system, the battery being grounded, trouble was experienced in the ignition system when starting on the battery. The company with which I am connected makes an ignition system that operates with or without a grounded battery, it does not make any difference. We can arrange it in any way desired, and that objection would not have any weight so far as this particular system is concerned.

I agree with the argument of Mr. Churchward, and the other gentlemen, in favor of three units. The starting and lighting are entirely different, and should be kept separate on account of the difference in the characteristics of the machines, and it is very evident to one who has gone over this problem that you can build the two individual machines, and get higher efficiency out of each one, than you can by combining the two into one machine. It has been my experience, too, that the simpler you can make a piece of apparatus, especially a thing you put into an automobile, the better off you are; because when it goes into the hands even of the car builders, it is surprising the things they will do to it. The electric motor-starting system has received a black eye, on account of the complications put in, in all the early systems, and it is now being recognized that these complications must go.

There is one point, on the last page of Mr. Churchward's paper, that is a little misleading. That is where he states that the difference between the weight of the batteries in six-volt and 12-volt systems will be 10 per cent. That is, the increase of weight will be approximately 10 per cent, or as much as the weight of the generator unit itself. Now, if he has a generator that weighs 11 lb. (5 kg.) his statement is correct. Otherwise it is not correct, because you can look in the catalogs of prominent automobile battery manufacturers, and you will find that a 100-ampere-hour battery weighs 59 lb. (26.7 kg.), and a 50-ampere-hour weighs 70 lb. (31.7 kg.), a difference of 11 lb. Any generator suitable to charge such a battery does not weigh less than 20 lb. (9.1 kg.).

Mr. Waller states that the battery should be capable of taking the maximum output of the dynamo indefinitely, and Mr. Churchward states that a dynamo which was giving enough current to take care of the lights, would in time overcharge the battery. I think that Mr. Waller's statement is nearer correct than the other in that respect.

Harold Goodwin, Jr.: Taking a previous speaker's objections to the single-wire system as premises, the question may be discussed from the experience of lighting companies. People generally do not test electrical apparatus for grounds until trouble occurs. Therefore, one side of a two-wire system

might be grounded and the automobile would continue to run practically on the one-wire system with all its objections till the second side became grounded. The installation of indicating test lamps to avoid this, would lead to questions and complications worse than the original trouble. Therefore, it would seem that one well-insulated wire with simple wiring will probably be the victor.

C. E. Wilson: I have noted a number of points in the paper by Mr. Churchward, principally in the comparison of the clutch and differential series generators, to which I wish to call attention.

1. The tapering charging current shown in Fig. 1 of the paper is claimed to be due to the fact that the generator is of the clutch type, and the statement is made that the charging current will decrease from ten amperes to about four or five am-

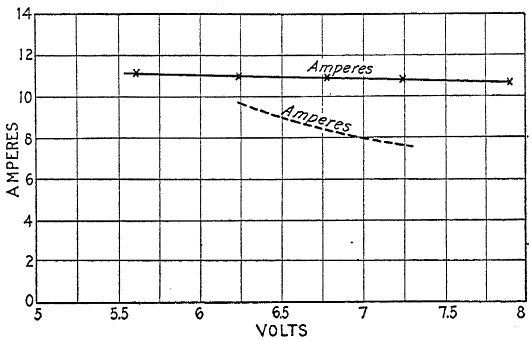

FIG. 4—AMPERES CHARGING CURRENT OF SLIPPING CLUTCH TYPE GENERATOR AT VARIOUS VOLTAGES

Solid line curve, test at constant temperature.
Dotted line curve, replotted from data in Fig. 1 of Churchward paper.

peres when the battery is fully charged, that is, to a voltage of approximately 7.75 volts. A test was made on one of these clutch type generators at variable voltage and the results are shown in Fig. 4 of this discussion. In covering a range from 5.5 to approximately 8 volts the charging current is only reduced about one-half ampere. This test was made with the generator charging a battery, with a booster machine connected in parallel with the battery, thereby making it possible to change the voltage through a wide range. This made a quick test possible and eliminated the effect of heating in the clutch type generator. Comparing the results of this test with Mr. Churchward's curve shown in his Fig. 1, it is evident that the decrease in charging current is due to the heating up of the clutch type generator and is not characteristic of the clutch type generator only. This same effect is noted, possibly to less extent, in the generator of the bucking series coil

type. In fact, a decrease in the charging current from ten to four or five amperes, as stated by Mr. Churchward, caused principally by the increase of resistance in the shunt field and the armature windings, certainly means an excessively hot machine.

2. In showing a typical regulation curve of a generator with bucking series field Mr. Churchward shows (Fig. 2 of the paper) a very poor regulation indeed. On increasing the charging current from 4 to 7.5 amperes the curve shows an increase in voltage from approximately 6.9 to 7.5 volts. In Fig. 4 of the paper, for the same change in charging current a change in the

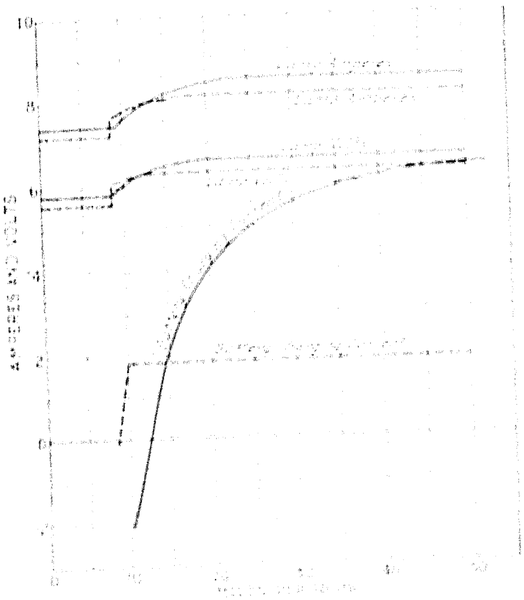

Fig. 5—Regulation of Automobile Lighting Generators

Solid line curves, bucking series field type.
Dotted line curves, slipping clutch type.

voltage from 6 to 6.1 is shown. As this rise in voltage with increase in charging current is due almost entirely to the battery, the increase in voltage should be the same in both cases and not as shown in the two figures. From tests on the two machines which the writer has made personally under the same conditions of battery load, lamp load, etc., the regulations of the two machines are as shown in Fig. 5 of this discussion.

3. In Fig. 3 of Mr. Churchward's paper no data are given as to the speed at which the generator is operating, and the lamp load at the different points. I cannot understand the change in the ampere and voltage curves shown at the end of

seven hours. Also the increase in current shown from the point at $3\frac{1}{2}$ hours to the point at 5 hours is very questionable unless the test was made under some unusual conditions, which I have been unable to duplicate.

4. In Fig. 4 of the paper a current curve is shown increasing from 4 to 7.5 amperes and holding this value for all higher speeds. The title of Fig. 4 is, "Voltage at lamps at different speeds." I do not understand how there can be a voltage at the lamps unless the lamps are turned on, and from tests which I have made on the most recent of these clutch type generators, the current when the lamps are turned on is not 7.5 but more nearly 4 amperes. Probably this same point was overlooked in Fig. 2 of the paper, where the regulation of the differential series generator is shown. It should be re-

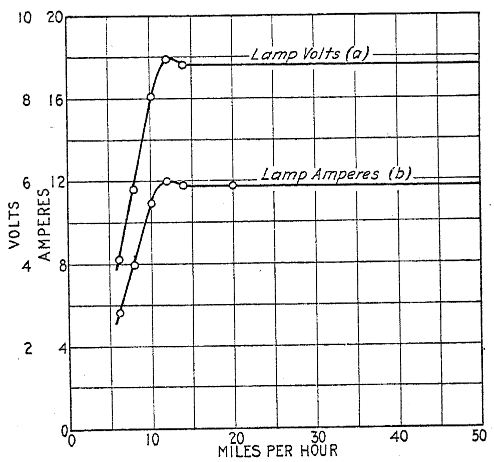

FIG. 6—REGULATION OF SLIPPING CLUTCH TYPE GENERATOR, WITHOUT BATTERY

membered that the voltage obtained at the battery without lamp load fluctuates more widely than when the lamps are connected in circuit, for when the lamps are turned on, the battery charging current at a given speed, and thereby the battery voltage, is reduced.

5. In Fig. 5 of the paper the lamp volts and amperes are shown with the generator disconnected from the storage battery. On making this same test on a clutch type generator of recent design, the regulation was as shown in Fig. 6 herewith. This voltage of approximately 8.75 at all car speeds above 12 miles (19.3 km.) per hour would undoubtedly burn out the lamps in a very short time and make operation on the generator without the battery impracticable. In fact, this point is of very little importance, for in the case of a battery of recent make

with proper terminals, etc., and a good job of car wiring, it is practically impossible for the circuit from the battery to the generator to become disconnected accidentally.

6. In Fig. 6 of Mr. Churchward's paper the performance of what we might suppose to be a typical starting motor is shown. No mention is made of the voltage at which these curves were obtained. The motor operates on a six-volt storage battery whose voltage, especially if the battery contains only 50 per cent or less of charge, drops very rapidly at high currents. As a matter of comparison, I have shown in Fig. 7 herewith a test on a starting motor, of the type described by Mr. Churchward, on the actual voltage which can be obtained on a car. This motor was of the four-pole circular frame type and weighs about 45 lb. (20.4 kg.). The motor whose curve Mr. Churchward shows differs so widely from this standard

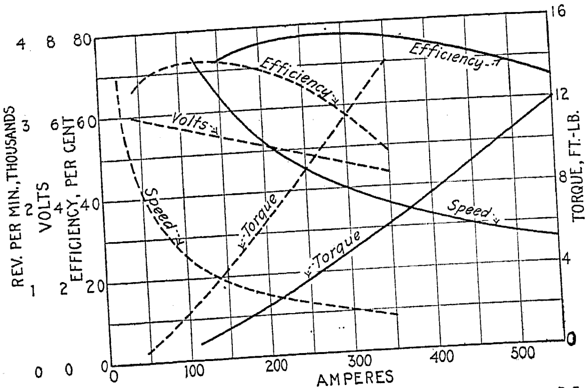

FIG. 7—PERFORMANCE OF AUTOMOBILE STARTING MOTORS

Solid line curves, standard 45-lb. starting motor.
Dotted line curves, performance of motor shown in Fig. 6 of Churchward paper, replotted for comparison.

starting motor that it must be very large and heavy or have some unusual features which should be explained. Another point worth mentioning is the fact that five or six hundred amperes starting current cannot economically be drawn from an 80- or 100-ampere-hour storage battery.

Benjamin F. Bailey: When engineers first began work upon the problem of applying electric lighting to the motor car, most of them proceeded upon the principle that the outfit should be a miniature reproduction of a large storage battery station. The writer of this discussion, on the other hand, has always worked upon the assumption that the simpler the apparatus, provided it would operate, the better. This attitude naturally led to the adoption of the differentially compounded generator. It will unquestionably operate. It involves no moving parts in the regulating apparatus, and the chances of trouble are,

therefore, very remote. There are absolutely no adjustments to be made, as there is nothing to get out of adjustment.

The next problem was to devise a method of connecting and disconnecting the generator from the battery at the proper times. It was desired that this apparatus should be comparable in simplicity with the generator, namely, it must be so simple that it could readily be understood by the average owner or garage man, it must be non-adjustable, and as far as possible, it must be infallible. Particularly, it must never fail to open the circuit when the engine comes to rest.

To secure these advantages the writer was forced to abandon the usual procedure of connecting the generator to the battery when the *voltage* was correct, and instead, make the connection when the *speed* was right. As soon as the connection is made the voltage of a differentially compounded generator automatically adjusts itself, for reasons which it is unnecessary to discuss here.

The means for doing this is the mercury switch shown in Fig. 8, herewith. The construction is nearly self-explanatory. It may be pointed out, however, that the containing shell is without joints, except where the threaded sleeve passes through the shell. The mercury never touches this joint, except possibly at the instant when the switch opens, due to the stopping of the engine. There is, therefore, no trouble from leakage. The contacts are of steel, and even after thousands of breaks show no corrosion. This switch is mounted on the generator shaft inside the housing, and the complete unit, including regulating devices and cut-out, is therefore self-contained.

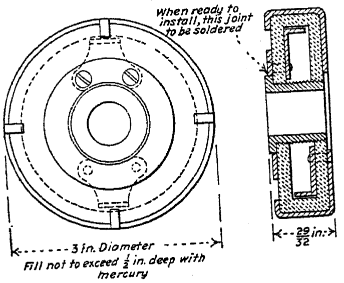

FIG. 8—ASSEMBLY OF MERCURY SWITCH

The writer believes it will be conceded by all that this arrangement leaves little to be desired from the standpoint of simplicity and reliability. It remains to consider what disadvantages, if any, we suffer as compared with the more complicated constant-potential systems. Mr. Churchward mentions five points in favor of his system, in which approximately constant potential is secured by operating the generator at approximately constant speed. A centrifugally operated slipping clutch is inserted between the engine and the generator.

Mr. Churchward's first point is that a constant-potential system charges the battery at a high rate when the battery is low and at a low rate when it is high. The charging rate of a so-called constant-current system is nearly the same irrespective of the charge. Thus there is a small waste of power, and the battery solution loses water faster than would other-

wise be the case. The first consideration is almost trivial, since the cost of the added power to develop the wasted power is too small to consider. Probably it is necessary to add distilled water more frequently to the battery, but the writer has now operated his car for over two months, during which time he has driven over 1000 miles (1610 km.) without adding a drop of water to the battery. The battery had stood without attention and without the addition of water for about two additional months before installation in the car. This is not recommended as a reasonable way to treat a battery. The writer merely wanted to see what would happen to a battery subjected to unreasonable use.

Mr. Churchward makes the statement that the efficiency of a constant-speed generator with slipping clutch is higher than that of a "bucking field" generator. With the former machine, if the constant speed is say 800 rev. per min. it is entirely possible that the driving member of the clutch is revolving at 3200 rev. per min. The torque on the two members of the clutch is the same and the clutch efficiency is 25 per cent. The combination efficiency would be not over 60 per cent of this, or 15 per cent. Actual tests of the system I am describing shows an efficiency of not less than 50 per cent at the above speed, and a somewhat higher efficiency at lower speeds. It must be remembered that the core loss does not increase in proportion to the speed, since the flux is weaker at the higher speeds.

The point is also made that it is possible to operate a constant-potential system with the battery accidentally disconnected. Undoubtedly this is so, but it should be pointed out that the same is true to a certain extent of a properly designed constant-current system. The writer finds that for speeds between 15 and 30 miles (24 and 48.2 km.) per hour, the lighting is satisfactory, and no difficulty would be experienced in getting home with the light generated in this way.

The company with which the writer is associated builds only six-volt systems. We believe that a somewhat more efficient motor may be built for 12 volts, since the commutator loss will be less, but are inclined to think that the greater weight of the 12-volt battery more than makes up for this.

The question whether it is better to have the generator and the cranking motor separate units or to combine the two is still an open one. The writer has designed and built both types. There is little difference in weight. The single-unit system is more convenient from the standpoint of the operator, since, as usually applied, no shifting of gears is necessary, this being accomplished automatically by the mechanism. This is not, however, an invariable rule.

With the two-unit system, it is believed that it is preferable to design the motor powerful enough so that only a single reduction gearing need be used. This is usually accomplished by the

use of a pinion on the motor shaft and a gear bolted to the flywheel or cut in the face of the flywheel itself. This requires a larger and more powerful motor, but the much higher efficiency (due to the lower gear loss) and the saving in the weight and cost of the gearing, will more than offset this. The total gear reduction would be about ten to one.

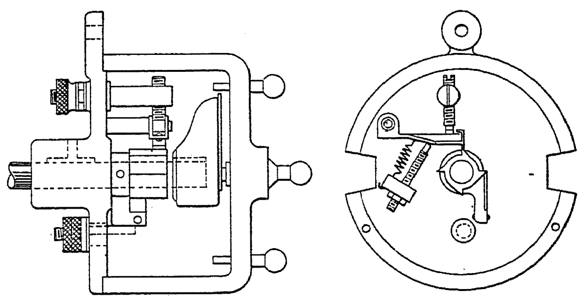

FIG. 9—ASSEMBLY OF TIMER AND DISTRIBUTOR

I am a strong believer in the use of the same system which supplies power for lighting and starting, for ignition also. Since it dispenses with a number of the parts of the magneto it can be made more reliable than the latter. Two strong points in its favor are that it can supply a strong spark even at zero speed, and the fact that the spark advance on a properly de-

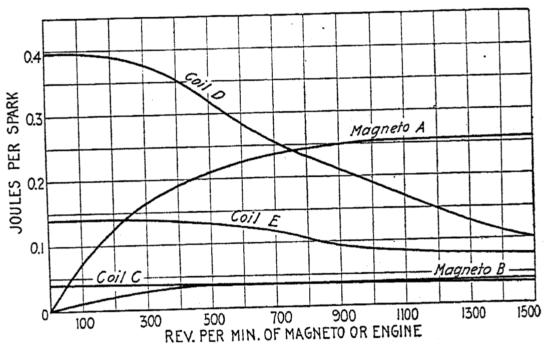

FIG. 10—COMPARATIVE OUTPUTS OF VARIOUS IGNITION SYSTEMS

signed system is absolutely unlimited. This is a point against the magneto which is often not given the attention which it deserves.

In Fig. 9, herewith, is shown the mechanism of the ignition device used in the system I am describing. This arrangement gives a quick break, the speed of the break being absolutely independent of the speed of the engine. Provision is made for

the possibility of a momentary backward rotation of the engine by the use of a double ratchet arrangement applied to the cam.

The arc of contact is constant, and therefore the time of contact is greater for low speed. To avoid too great a difference in the strength of spark at low and at high speeds a "quick" coil is used so that time is afforded for it to become practically saturated even at high speeds.

A great number of tests have been carried out upon different ignition systems, to determine the output in joules per spark. This, as pointed out by Mr. Conrad, is not entirely a fair comparison, since not only the total energy per spark, but also the rapidity with which it is liberated, is of importance. In other words, what happens after the gas has been ignited is of no importance. Our knowledge regarding some of these points is rather limited, and perhaps the total energy per spark is as good a measure as any. The curves shown in Fig. 10, herewith, give the results of some of these tests. Coils *D* and *E* are of the writer's design. Magnetos *A* and *B* are both well-known makes. Coil *C* is that of a well-known constant spark system. All of these outfits gave good results in service, and all except coil *C* have been personally tested by the writer upon actual cars. Coil *D* is the one the writer uses for general purposes. As a matter of fact, coil *E* seems to give as good results, except possibly in starting a very cold motor. Magneto *A* is a very large one weighing over 30 lb. (13.6 kg.), and is intended for low-speed work. The magneto outputs are those obtained at the best point of spark advance. In actual service, at high speed and large angle of advance, the output would be much less.

Kingston Forbes: Let us look at the question of starting and lighting an automobile from the automobile engineer's standpoint. When the automobile manufacturer has decided to install electric lighting and starting apparatus on his cars, he turns to the trade papers, and finds there are some 42 different outfits being marketed by electrical manufacturers throughout the country for this purpose. Not being an experienced electrical engineer, he has to depend on the recommendation of the salesman-engineers, and he is confronted with the problem of whether to use a 6-volt, 12-volt, or 24-volt starting and lighting circuit. The essential requirement in an automobile is to get it as simple as possible. The multiplicity of control in the present automobile is greater than a great many of the operators and laymen care to handle. This makes the simplicity of the electrical apparatus an important consideration. The use of the 12-volt or 24-volt system necessitates complicated wiring and switching, and the automobile manufacturer does not like to confront his customers with this proposition.

Studying this situation carefully, it seems to me that the single-wire system affords the greatest simplicity in respect to the lighting system of the car. In looking over the chassis of a car, if there

is a multiplicity of wires incident to the lighting and starting system it frightens the admirer of the automobile. With the use of the single-wire system, it is possible for the chassis and body to be so wired that by three disconnections the body can be disconnected from the chassis, and the chassis can be so wired that all visible evidence of the wires is practically eliminated.

Another problem connected with electrical apparatus is where to put the various units. There are two or three alternatives offered to automobile engineers—the single-unit system, the double-unit system, and the three-unit system. It seems that it is not advisable to complicate matters to the extent of having one piece of electrical apparatus to supply the demands of ignition, lighting and starting. It seems to me that the electric starting motor in its simplest form, series-wound, would take care of starting, and, going a little further, it would seem that a generator, with a combined apparatus to take care of ignition, should be the logical consequence. This cuts down the electrical equipment to two pieces of apparatus, which, to go a little further, can be coupled up directly to the water pump shaft. By installing the generator like an ignition outfit, connected to the pump shaft, we get a direct-coupled system which is very easy to install when the chassis is being assembled.

As regards the installation of the starting motor, different problems are presented to us, inasmuch as the position of various other parts of the engine is fixed in accordance with the designer's ideas. This makes it necessary for the starting motor to be placed in such a way that it will not interfere with other parts of the chassis.

Still another problem which confronts the automobile engineer is the mode of operating the starting motor—whether by means of a simple switch or a complicated set of levers and overrunning clutch and gear reduction sets. We look to the electrical engineer to simplify the application of starting motors, and the automobile engineers must coöperate.

Up to the present time considerable trouble has been experienced with starting switches to handle comparatively low voltages and high amperages.

Alexander Churchward: I have been trying for four years to get a discussion openly on the slipping clutch machine. All I could get was the statement, "We do not use slipping clutches". But the fact remains that between thirty and forty of the leading automobile manufacturers throughout the United States and Europe are being supplied with the slipping clutch machines and these companies find by actual test that they cannot get similar good results with any other appliance. They would like to be able to dispense with these slipping clutches if they could, but they cannot.

As to criticising the slipping clutches in regard to mechanical adjustment, all I can say is that they do not need as much and as frequent adjustment as the vibrating regulator machines now

in the market. I have seen them tested against the slipping clutch machines which they claim wear so badly, when the latter stood up ten times as long without adjustment as the vibrating regulator machines. That is why so many companies use the slipping clutch machines.

Alfred E. Waller: One of the most deceptive problems the automobile engineer has to face is the old question of the single-wire system with ground return. I believe that most people who recommend the single-wire system are not familiar with its application in automobile work. It is obvious that the metal car frame is capable of carrying current far in excess of the amount required by automobile lamps. The point is that it is not an easy matter to get the current from the lamp terminals to the car frame and from the frame to the battery, due to the difficulty of obtaining good ground connections which will not corrode.

In motor car headlights, as they are made at the present time, the socket that holds the lamp is brazed or otherwise securely fastened into a parabolic reflector of spun metal. The reflector is held in the headlight by an expanding ring which fits in the front cover of the lamp or by some other equivalent means. There is no doubt that the current may be carried satisfactorily on any kind of a continuous metal path, but this method gives a conductor full of joints which may or may not make good contact. You have to start with a socket and get from the shell of the socket to the reflector, and from the reflector to the lamp frame through the expanding ring. Then the circuit runs through the hinge and frame of the lamp to the lamp bracket, then to the car frame. The alternative is a ground wire from the socket to the car frame, and such a wire must not be merely clamped against the frame because it will rust and corrode and consequently make poor contact. You have to drill the car frame and tap it and secure the ground wire by means of a screw set up tight so that you get a continuous metal path which cannot, under any conditions, be affected by corrosion.

It was stated in the discussion that the wiring could be simplified by using a single-wire system. Does it make any difference whether you run two wires in the same sheath or a single wire? The cost of the extra copper for the two-wire system is insignificant. As far as large users of power are concerned, it should be remembered that all of the street cars of New York City are using the metal return. No buildings are wired with a ground return. Very few boats, and none of recent construction, use ground return. The United States Navy has absolutely specified against it after trials which showed it to be unreliable and costly.

Finally, if armored cable is used with the sheath forming the ground return, you have practically the two-wire system with one conductor entirely uninsulated, so that the system is operating at 50 per cent efficiency under the best conditions. I do not understand how any automobile engineer familiar with the difficulty in carrying current through ground connections can be deceived in the matter.

Frank Conrad: The only objection made to the bucking series type of generator was that it does not give the tapering charge described as being desirable for charging the battery. In Mr. Churchward's paper the first advantage given to the clutch type generator is that it charges a battery as it should be charged; that is, with a comparatively large current when the battery is low and empty, tapering off to a small charging rate when the battery is full and at the gassing point.

Fig. 1 in Mr. Churchward's paper gives for the initial charge 9.6, and for the finish about 7.75 amperes, and the battery which will be required for a car installation with a starting motor would stand a continuous rate of 10 amperes, as pointed out by Mr. Waller. It is therefore evident that the initial charging rate obtained by the clutch type generator is no real advantage. Any tapering of the charge is probably due to heating rather than to increase of voltage. Comparative tests have been made of a bucking series generator and a clutch type generator, operated with a resistance load instead of a battery, so that the voltage was constant. The results showed that the actual taper of the bucking series generator is of a greater percentage than the clutch type. That effect is due to the heating of the shunt coil.

In his comparison with the high-voltage batteries, I believe (and the point has been brought up before by another speaker) Mr. Churchward takes a 6-volt battery and divides the plates in two. Of course, if the battery maker were making this battery he could use a different plate to make the capacity even, and then the weight would not be so great.

If the actual increase of weight was 10 per cent, with the average generator with which I am familiar, that would mean a battery weighing 200 lb. (91 kg.), probably 250 lb. (113 kg.).

Alden L. McMurtry (by letter): Mr. Waller's statement that "in practically all instances the system of running two wires to each lamp and fixture has been adopted," may be criticised. Automobile engineers are adopting the one-wire system on account of simplicity, stability, and freedom from electrical troubles.

The automobile wiring problem is entirely different from that pertaining to the street car, steamship or railroad coach. The longest circuit is less than 100 in. (254 cm.), and the troubles encountered are all mechanical rather than electrical. The drop in voltage is less than in the average two-wire system, and the supposedly "poor connections" in the lamp are theoretical.

I have made numerous tests on this subject, and my reasons for advocating the one-wire or grounded system are as follows:

(a) It is stronger mechanically, especially in regard to receptacles; simpler for average operator to locate wire troubles.

(b) It will stand a higher insulation test.

(c) The average electrically-lighted automobile has one side of the battery grounded to the ignition system, and has there-

fore actually a one-wire system, although subject to all the troubles of the two-wire system.

(d) The connections are larger, insuring better contacts at the lamp base.

(e) The amount of current is too small to cause electrical troubles, at connections to the frame of the car.

Inspection of automobiles that have the one-wire system will disprove all arguments used against it.

A point in the discussion of high-voltage systems which is of great importance is the size and form of the tungsten filaments. The six-volt lamp has a small concentrated filament, which makes it easy to focus the lamps. Higher voltage means a longer filament of smaller size, and therefore it will be a difficult matter to focus a searchlight properly. In England, where the 12-volt system is almost universal, the various automobile lamp makers have various forms of reflectors which require a special type of incandescent lamp. This not only lessens the effectiveness of the lamps, but restricts users to lamp renewals supplied only by one manufacturer. The candle power of the tungsten lamp is a secondary consideration to the form of the filament. The distance to which useful light is projected ahead of the automobile is governed by the intensity of the lamp. Lamps of higher candle power cause a greater drop in voltage, and therefore the intensity of the light, and the distance it is projected, is less, while the large area of the filament gives a beam of light of a slightly greater angle.

Some of the arguments against the clutch type of generator are not based on fact. I have personally tested this type of generator over a period of more than 600 hours' continuous running. The wear on the clutch surfaces was not perceptible, owing to the fact that the surface requires very little pressure. I have on my car a clutch type generator, which has been in constant use since December, 1910, and the only attention required was for lubrication, which was needed about once every six months. The rate of current output has decreased approximately seven per cent during this period.

Frederick S. Dellenbaugh, Jr. (by letter): In the early development of any new apparatus correct operation and reliability are of prime importance and the criteria of success. But as the art develops refinements in all directions are introduced and one of the main aims is improvement in efficiency.

This is clearly to be seen in the present case with electric lighting generators for automobiles, and more attention is being given to decreasing the power losses. The gas engines themselves are cut down in every detail to add a little to the efficiency and therefore the choice of a lighting generator, other things being equal, should be governed by the requisite input.

Though of course the most dependable comparisons are based on actual tests, provided they are accurate and made under conditions actually duplicating the ordinary service, it is in-

teresting to investigate the theoretical considerations of the case, as they show what should be expected and, if all factors are included, give approximately correct results.

Except for variations in individual design, the most widely differing types of lighting generators are the constant-speed and the variable-speed types. All the machines built can be included under these heads. In any generator the losses are:

Copper losses due to resistance of windings.

Core losses due to hysteresis and eddy currents in armature core.

Windage losses and friction losses.

Minor losses under load which are practically negligible.

In addition to these we have transmission loss in applying power to the generator.

Taking up first the variable-speed generator, the losses in windings are practically constant as the current in most types is constant.

The windage and friction losses increase with the speed. The windage is very small so that we should expect these losses to be nearly proportional to the speed. In this type of generator the transmission loss can be considered as part of the friction loss.

The variation of the core loss is more complex. Compared to the wide range of speed the voltage can be considered approximately constant.

If ϕ = field flux,
n = speed,
v = volts,
B = flux density,

then volts $= K_1 n \phi$

K being proportionality factor.

Or
$$\phi = \frac{K_1 V}{n}$$

Core loss $= K_2\, n \times B^{1.6}$ approximately, as the eddy current loss is a very small percentage of total.

$B = K_3\, \phi$ in any one machine, dimensions being constant. Substituting,

$$\text{core loss} = K_4\, n \times \phi^{1.6} = \frac{K_5\, n \times V^{1.6}}{n^{1.6}} = \frac{K_5\, V^{1.6}}{n^{.6}}$$

Thus, if voltage is assumed constant, core loss will decrease slightly as speed increases. Taking the sum of the losses:

Total loss = Core loss + copper loss + windage friction

$$= \frac{K_6}{n^{0.6}} + K_7 + K_8\, n$$

If we assume K to make losses equal we have:

$$\text{Total loss} = \left(\frac{35}{n^{0.6}} + 1 + 10^{-3}\, n\right) K_9$$

If n = 1000 rev. per min., total loss = 3 K_9.

If n is increased to 3000 rev. per min., total loss = 4.56 K_9 or an increase of 52 per cent.

Thus, if efficiency were 50 per cent to start with, at 3000 rev. per min. it would now be 39 per cent, or the input would be increased 11 per cent. This is actually a little low, but serves for the purpose of illustration.

In the case of the constant-speed machine, on the other hand, all the losses in the generator itself remain constant and the transmission losses vary. The only successful constant-speed generator that we know of is the one described by Mr. Churchward in his paper, and this uses a clutch which slips above a certain speed. It is evident that for any stable operating condition the torque at the two adjacent faces of the clutch must be the same. The power developed or required is proportional to the torque times the speed, and therefore as the speed of the engine increases, the power supplied to the clutch increases in direct ratio, while the power required to run the generator remains the same.

Evidently, then, if the speed of the engine increases to three times that at which the clutch just begins to slip, the efficiency of transmission must be reduced to 33 per cent, provided it be considered 100 per cent with no slip.

Comparing this with the figures for the variable-speed generator, if we assume slippage to begin at 1000 rev. per min., and efficiency over all at this point 50 per cent as before, and losses $= 3K_9$, then the input = 6 K_9. At 3000 rev. per min., the input to the generator will still be 6 K_9, but, as shown above, the power on the high-speed side of the clutch must be three times this, as the torque is the same, and so the input there is 18 K_9. Out of 18 units only 3 are being used, as the efficiency over all is now 18.7 per cent.

From this it is evident that the constant-speed machine, whatever its advantages may be in other ways, is inherently extremely inefficient unless some device which will transmit power by transforming torque as well as speed be used, and the variable-speed machine has actually a fairly uniform range of efficiency over its complete range of speed.

John R. King (by letter): Referring to that portion of Mr. Waller's paper wherein he speaks of the necessity of regulating the control of the output of the lighting generator under varying speed conditions, and gives several methods of obtaining regulation, I would like to call attention to a type of generator developed in Germany during the years 1904 and 1905, by Dr. Emmanuel Rosenburg, and used in connection with a storage battery, for lighting railway trains. This apparatus is described in the *Electrical World and Engineer*, Vol. 45, p. 898; Vol. 46, p. 104, and the *Electrical World*, Vol. 48, page 918.

As automobile lighting requirements are similar to those of railway trains, it would seem that unless conditions of design for the smaller units interfere, this type of generator and lighting

ould be applied with success to motor cars. Briefly, n and operation of this type of generator are as follows: ature is the same as that in an ordinary direct-current , but the field construction is somewhat different, the es and frame having a small cross-section and the pole faces being considerably larger, spanning nearly the mature surface, and being notched and cut away at the oint along the line of the armature conductors. There le sets of brushes, one set being placed on the ordinary l neutral and the other set displaced 90 electrical degrees m. The brushes set on the neutral are short-circuited rent is collected from the displaced set. The simplest machine is one that is shunt-wound.

the machine is started the voltage increases in proportion the speed until the point of magnetic saturation of the cross-section of the pole pieces and frame is reached. further increase in speed, the flux in the field frame is htly increased, and the cross-flux created by the coils he short-circuited brushes tends to counteract this in- and to hold the current output constant, due to the large ld in the enlarged pole shoes. The result is that the machine iver a constant current with varying voltage conditions vide range of speed, or if the outside resistance is constant chine will deliver approximately constant voltage inde- of speed. Other conditions and refinements may be d by introducing a series field winding.

Presented at the Detroit-Ann Arbor Section Meeting of the American Institute of Electrical Engineers, Ann Arbor, Mich., December 5, 1913.

FACTORS DETERMINING A REASONABLE CHARGE FOR PUBLIC UTILITY SERVICE

BY M. E. COOLEY

Probably no question of greater importance confronts our people today than the relations of the public and the public service corporations. I refer to relations of a domestic character, rather than foreign, those which affect us as a nation considered as a family in which the interests of all of its members are, or should be, entwined, interwoven, in such manner that whatever is good for one is good for another.

Naturally in treating my subject I shall have in mind ideals which may require years for their realization, but I shall hope to appeal to you with arguments based so firmly on actual facts that I shall not be accused of being academic. I shall endeavor to throw upon my subject the light of nearly fifteen years of experience in the investigation of public utility properties, and I shall hope to leave with you the impression that my views have been expressed with due regard to proper perspective. That is to say, I shall hope to avoid being accused by anyone of even *appearing* to favor one side of the question as against the other. My desire is to speak of what may be seen from the hilltop by any one who will divorce himself from the interests of either side, and try to look upon the problem with unbiased vision.

There are, of course, two sides to this question, as there must be in order that any question can exist. There is the side of the public and the side of the public service corporation. Today they are wide apart. They are wide apart for one principal reason, namely, ignorance. While it may be no disgrace to be ignorant, it is disgraceful to remain ignorant when so little education is required to dispel it. The education required is

not difficult; indeed, it is very simple; but the trouble is that very many of those who most need it are not willing to be educated. Various motives exist, which I will not discuss here, further than to mention that chief among them is a spirit of antagonism, akin to revenge on the part of the public, in localities where the opportunity exists for its manifestation.

It is, I believe, generally considered by the officers of public service corporations that they are, or rather were, themselves responsible for the unfriendly attitude of the public toward them which is now almost general in this country. The public service corporation has in the past proceeded on the theory that the words *public service* had no particular meaning, and that like any other corporation it was at liberty, and indeed had the right, to make as much money as possible out of its business. The public service corporation has in the past ignored the fact that its right to do business is a public grant, a grant which in the very nature of it precluded others from engaging in the same business in the same locality. True, in theory at least, others might be admitted to the field and thus create competition, but practically it has not worked out that way. Ordinarily there is not enough business for two, and even if there were, great inconvenience is likely to result; as for instance in the use of two telephone systems, two waterworks systems, and several street car systems in the same city. It is much to the advantage of the public, both in convenience and expense, to have a single utility of the different kinds serve it when that service can be had on fair terms.

What are fair terms? That is what is partly meant by the words *reasonable charge* in the title of this paper. I say *partly* meant. In the broad sense they may be synonymous. To illustrate: The service rendered by a public service corporation may be very poor without any good excuse for it. In such a case a reasonable charge would be less than when the service was entirely satisfactory. Careless or unintelligent management, or a desire to increase the dividend rate, would lead to this result. Again, the service rendered may be very poor and yet be the best possible and keep the business alive; that is, were the rates higher a better service could be rendered. This may be found in small towns where the extent of the business will not support anything better. Further, the service may be very unsatisfactory and still be the best possible to render regardless of rates; that is, physical conditions may limit

the ability to render satisfactory service. This may be found in large cities, an example being a street railroad system which can not be extended except by building elevated or underground systems.

Fair terms, then, means fair service, or the best possible under the conditions, to the public on the one hand, and a reasonable charge for that service to the corporation on the other hand. They are, or should be, the two members of an equation which are equal to each other. Like an equation, given the service demanded and certain other factors involved, the fair rate, or the reasonable charge, can be readily determined. It is these factors we come now to consider. They embrace, first, the capital investment upon which the interest return is made either in the form of interest or dividends, or both; second, the operating expenses which include maintenance and repairs of all the elements of the physical property, and taxes; third, a depreciation fund out of which can be replaced elements of the physical property which are worn out, or have become obsolete, so that they can no longer be used economically; and fourth, a sinking fund to provide for the loss of the capital due to depreciation, or the difference between the cost of the property when new and when disposed of at the expiration of its franchise life. Let us take them up in order, capital investment first.

It should be understood at the outset that no capital can be made available for a public utility, or for any other business, for that matter, without a sufficient return on the money to tempt its investment in the business. Capital obeys the law of supply and demand like any commodity. Thus, if capital be invited for investment in a service which is desired by the public, then the public must expect to pay the price in the form of interest or dividends which is necessary to secure it.

However much in the past capital may have been tempted into the field without invitation in the hope of large returns, those days are rapidly disappearing; and before very long, if not now, we shall be obliged, not only to extend an invitation, but to offer inducements to bring capital to our door. Those inducements must be not only a fair return on the capital investment but a welcome guaranteed throughout a term of years. Capital may be compared with the guest in our household. While she bides with us she is entitled to the treatment accorded to a guest. She may have worn out her welcome but at the same time have become indispensable to our domestic affairs, so that

we must continue to suffer her presence. We, the publi cannot invite the guest and then while she is with us slap h face; on the other hand, the guest cannot with impunity proce to rob us once she is in our home.

There is at present a very natural distrust on the part of t public. Capital in the past having very often been self-invite and having been at first welcome, then tolerated, has final worn out both welcome and toleration. The logical result, o might think, would be to get along without capital. But course that would be impossible. Whether the utility be bui and operated by the public or by a corporation, capital necessary. It is true that for a municipally owned utility, capit may be had on more favorable terms with the security which th public can offer; but it does not follow that the service render *would* be at correspondingly low rates or reasonable charges. I *could*, perhaps, but the experience of the past favors the beli that such expectation would be utopian rather than practical.

The time is coming, if not already here, when it will make n difference whether capital be invested under the direct securit afforded by a municipally owned utility or the more indirec security afforded by a franchise to a corporation. This time wi have arrived when the public comes to understand the element of cost, and all of them, which enter into the construction of public utility plant. Those elements of cost are the same, o substantially the same, whether the plant be constructed by th public or by the corporation. The public must have a boar intrusted with the construction and management of the utility This board corresponds practically to the corporation's boar of directors.

The board, whichever it may be, becomes the agent of th public. It makes the preliminary investigations, employs lega counsel, real estate men to procure the necessary right-of-way conducts condemnation proceedings, obtains property consent and attends to all matters connected with the proper launchin of the project. It employs engineers to prepare the plans an specifications, invites bids, awards the contracts, and look after the work during the construction period. It makes ar rangements for the necessary funds to finance the project, th necessary working capital, and finally, after the work of con struction is completed, puts the plant into operation.

Before its work has been done completely, the business must b thoroughly established; that is, converted from an inanimat

to an animate condition. The earnings from operation must as speedily as possible be brought to a point where they will support all of the expenses. During the period of insufficient earnings, the deficits must be cared for. When the earnings become sufficient to meet all expenses, including interest on the cost of the property, the utility may be said to have become fully a *going concern*.

In all of this work the duties of the board or city officials representing the public, or of the officers representing the corporation, have been the same. The elements of costs have been the same. The principles involved have been the same. The only difference has been one of degree on some of the items, as for instance, less difficulty, possibly, in securing rights-of-way, and more favorable terms in financing. But as already stated, these advantages may in the ultimate results be more *apparent* than *real*. That phase I have no intention of discussing in this paper.

The principal cause of the difference of opinion between the public and the public service corporation, as I have come to see it, lies in the failure of the public to comprehend all of the elements of cost entering into the construction of a public utility plant. Not only that, but a failure also to understand all of the elements of expense which must be incurred in operating the property and maintaining its integrity, once the plant has been built and the business established. The corporation itself is only beginning to understand some of these things. Its officers intrusted with the management of the property have been obliged to make the best of things, striving on the one hand to earn the dividends called for by the stockholders, and on the other, to maintain the property so as to give satisfactory service. Without in any way excusing the corporation from its sins of the past, or of the present where they still exist, the trouble is now understood by the corporation, partly at least; and it must be conceded, I think, that just at present the fault lies more with the public than with the corporation. Let us now take up the elements of cost constituting the capital investment.

It will be easier of understanding if individuals will consider themselves a party to the enterprise. Assume for instance, that you are one of a number of men brought together to consider the building of a public utility property. What is the first step? Naturally you will all want to know whether the project is feasible. This will always involve preliminary investigations,

the sounding of public sentiment to know to what extent the proposed service would be demanded, what concessions would have to be obtained in the matter of property consents and the conditions under which a franchise could be obtained. If these inquiries have resulted favorably, the next step would be to employ engineers to look over the field and make preliminary estimates of cost and determine upon the feasibility of the project. With the information thus far accumulated the bankers must be consulted to determine whether the necessary money can be had. At this point the project may fall through, as there may not be a sufficient promise of financial return to induce capital to come into the enterprise.

All of this preliminary investigation has involved expense which must be borne by someone. It may run from 0.2 to 0.5 per cent of the cost of the proposed property. In case of failure to go further it would fall upon the individuals taking part in the investigation. They have gambled and lost. But should the future promise be great enough to interest capital *mildly*, let us say, then the banker might be induced to gamble a bit, and by being given sufficient odds in the way of discount on bonds and blocks of capital stock depending for their value on future earnings, be induced to come in. The less of gamble there may be, the less the odds demanded by the banks; but at the present time these keepers of the vital life of all business enterprises must, like the well-fed trout, have bait of some form on the hook to interest them at all. Not so, however, with the rank and file who, like the hungry bull-head, bite at anything, even in the dark, if only the light of a candle be exposed to show in the faintest outline the nature of the bait. But public utility properties for the most part are not financed by the rank and file, but by bankers and trust companies. It is, therefore, a real " condition, and not a theory ", which confronts the promoter when he seeks to finance a proposition.

If finally the preliminary work has resulted in the determination to proceed, there comes the organization of the company, the employment of legal counsel to draw up the necessary papers, the procuring of franchises, the obtaining of the necessary property consents, the securing of the right-of-way, by purchase or otherwise, the employment of engineers to make the final surveys and prepare the plans and specifications, the bidding and award of contracts. The actual work of construction then begins.

It is at this point that the public conceives the cost of the

property to begin; and for the reason that the average citizen, skilled as he may be in the work of his own pursuit, has little or no knowledge of the skill required in another's pursuit. Yet this average citizen must be consulted because the project is a public utility. It furnishes him heat, light and power, transports him to his business, and provides him with other fixed necessities of life. This being so, let the condition be met, and first of all let this average citizen be educated to understand the requirements which must be met if he is to be furnished these necessities of our modern civilization. Once he understands there will not be, so far as he is concerned, any further trouble. The average citizen is fair-minded, and asks for only the square deal.

There is, however, another type of citizen who, however much explaining there may be, persists in seeing things his own way. He may be a self-appointed guardian of the people's interest; sincere enough and honest enough, but too often his zeal results in confusion of understanding, if not perniciousness. Another type belongs to the political class. He sees gain in one form or another if he can keep alive the troubles between the public and the public service corporation.

There is no greater service to be rendered the people of our country today than that which could be rendered by the newspapers if they would but go at this matter with the idea of acquainting their readers with the facts on both sides. I mean that they should not treat the quarrels between the public and public service corporations as items of news merely, but detail men on their staffs to make a study of the question involved, bringing to their aid the skill of the accountant, the engineer, the manager, the public officers entrusted with the affairs of these corporations, the business man, and the man who has devoted a lifetime, it may be, to a study of this class of problems. This work should not be done in a haphazard manner, but systematically and with one object in view, namely, to bring about as speedily as possible a clear understanding of all the facts on both sides. Such a work by our newspapers would not only add to the sum total of our happiness, but promote the prosperity and welfare of the communities which they serve. I sometimes wonder why the proprietors of newspapers do not see that their own business is in the nature of a public utility, morally at least.

It is perhaps unnecessary to refer in detail to all of the different items entering into the cost of the physical property of a public utility. Such items as the following are in general capable of being classified in an inventory, and are readily understood:— Land for railroad rights-of-way, electric transmission lines, and pond flowage; land for the many kinds of buildings required, such as office and station buildings, round houses, car barns, power houses for steam and hydraulic plants; and for reservoirs, dams, waterworks, and gas plants. The buildings themselves, together with their furnishings and fixtures. The roadbed, rails, ties and bridges of a railroad; and the locomotive, passenger and freight equipment. The dam structure, water wheels, and generators of a hydroelectric plant. The boilers, engines and generators of a steam plant. The tunnels and pipe lines of a heating plant. The pumping engines, water mains, hydrants and distribution system of a water works. The machinery, gas holders, and distribution system of a gas works. The conduits, manholes and distribution systems of electic lighting and power plants. The switchboard, machinery and apparatus of a telephone exchange; and the wires, pole lines, conduits and instruments of the distribution system. All of these items, and vastly many more, make up the physical structure of public utility plants. They are tangible, that is, they can be seen, counted, measured, weighed, and their costs determined. Materials and labor are the principal items in their creation and installation.

The plans and specifications of a utility plant having been completed, proposals for its construction are invited. The contractor figures the cost of every item as nearly as possible, adding various percentages to cover contingencies, that is, unforeseen difficulties of construction and oversights, some large and some small. He adds the costs of the necessary permits, the insurance required on the men employed and on the buildings during their construction; and finally adds another percentage on the whole for his profits. The propriety of these percentages in figuring the cost of work in advance is so apparent as to cause wonderment that any question should ever have arisen as to the equal propriety of including them in making an appraisal of a property at any time after it was built. Happily this ignorance concerning many of the physical elements has been dispelled, and there no longer is any question of allowing the necessary percentages to cover contingencies, insurance, contractors' profits, engineering and superintendence.

In amount the contingency percentages, varying on the different things from 2 to 20 per cent and upwards, may be assumed to average not less than 10 per cent. One half is usually applied directly to the items themselves, the other half as a percentage on the total cost of all the items. Insurance varies from 0.5 to 1 per cent. The contractor's profit should be estimated at not less than 10 per cent. Engineering and superintendence, like contingencies, varies with the different items from 2 to 10 per cent and over, an average being, say, 5 per cent. One half is applied directly to the items themselves, the other half, as a percentage on the total cost of all the items, including the contingencies and contractor's profits. If the insurance has not been included with the contractor's costs, it should follow after engineering and superintendence, and may then be combined with taxes in a percentage varying from 0.5 to 3.5 per cent. In the application of these percentages, only the *general* engineering percentage should be applied to land, the cost of which embraces its own particular expenses of acquiring, including damages, deeds of transfer and the like.

In case the contract has been awarded to a general contractor he may sublet the different parts to other contractors, each of whom includes in his bid contingencies and other items proper for his particular part of the work and his profits. In such cases the cost of the plant includes, besides the contingencies and profits of the sub-contractor, similar items for the general contractor. A general contractor responsible to the owners for the success of all building operations would probably demand and receive not less than 10 per cent of the cost of the entire work covered by his contract; and instances are known where the general contractor's profit has been large, 20 per cent or more. The measure of his profit is usually determined by the nature of the work, that is, the difficulties and uncertainties involved. The building of the Detroit River Tunnel is an example of where the general contractor made a large profit; but the uncertainties were such that it was not known in advance whether his profit would be large or small, or whether there would not be an actual loss.

Another method in vogue is to place all building operations in the hands of an engineering firm which makes all surveys, prepares the plans and specifications, and superintends the work from start to finish, making a charge therefore of 10 per cent on the actual cost of the work. This virtually amounts to a profit of 10 per cent, as the cost on which the percentage is based

usually includes the salaries and wages of the men employed in the engineering work, and all traveling and office expenses as well. It is known as the "cost plus a percentage" plan. The engineering firm may be likened to the general contractor with this difference: The former takes its percentage on actual costs determined after the work is completed; and the latter, on the estimated costs made before the work is begun. Obviously the uncertainties involved would cause the general contractor to guard himself by making liberal estimates.

We come now to discuss certain other expenses chargeable to capital, but which are not so well understood. Taxes during the construction period is an item usually overlooked by the public. Obviously, any real estate acquired by a corporation for public utility purposes would be taxed the same as similar property owned by an individual. Taxes not infrequently are also imposed on structures built, even before any use is actually made of them. One very common error of the public is to assume that if municipally owned there would be no taxes on a public utility property. True, there would be no taxes levied directly against the property, but there would be the indirect taxes which every taxpayer would have to meet. To illustrate: A public service corporation has to pay certain taxes on its property, and they may be very large. If this property be acquired by the city, it bears no taxes. The same amount of money being required to meet the expenses of government, after as before, it follows that the citizens must make up the amount formerly paid by the corporation. If, however, the earnings remain the same, there will be money to pay the taxes out of earnings. But in that case presumably the rates of charges for service would remain the same, so that one of the alleged benefits of public ownership would disappear. The item of taxes is, in an appraisal, frequently combined with insurance, the amount of the item then varying from 0.5 to 3.5 per cent.

The item of organization, administration, and legal expenses usually follows insurance and taxes and precedes interest during construction. As used by some, the term is rather elastic in being made to include all preliminary expenses, costs of promotion, certificates of necessity, mortgage tax, fees of incorporation, securing of franchises, and other general expenses. It is usually expressed as a percentage varying from 2.5 to 5 per cent, being applied to the sum of all preceding costs, including lands.

There arises in connection with many utility projects certain expenses which have come to be known as costs of promotion and promoter's profits. The terms themselves are rather infrequently used in appraisals, these expenses, if considered at all, being included under costs of administration. Administration is frequently combined with organization and legal expenses. Whatever may be said for and against costs of promotion and promoter's profits in the sense that they represent intangible elements in the nature of "rake-offs", there are, in a totally different sense, certain expenditures during both the construction period and the early operative period which are legitimate and necessary and best described as promotion costs. In the sense that a promoter forwards, advances and encourages, that is, contributes to the growth, enlargement and excellence of a utility project desired by the public, there can be no question that such costs are entitled to consideration in determining a reasonable charge for service.

As to a promoter's profit, its propriety may possibly be decided by considering to what extent one would be willing to contribute to a project, independent of its construction cost, to procure its establishment; or, were a utility now serving the public in some necessary capacity to be taken away, to what extent would you, as one served by it, be willing to contribute rather than lose it. Put it another way: A man says he can make a success of a utility the citizens want, or now have. You doubt its possibility but consent to a trial, and he does it. How much are you willing to compensate him for his energy and brains? This implies a conception free of bias, broad-gaged and just to all interests concerned, which can be had only by being fair and open-minded, and by carefully refraining fron reaching any conclusion in advance. Obviously no percentage could be given for promoter's profits, but appraisals in which the costs of promotion have been ascertainable indicate that a proper charge may be as much as 2 per cent. Its allowance must depend on circumstances, and if included as a separate item, it must of course be excluded from administration costs.

Interest during the period of construction is an important item often overlooked in the past. This means simply that the money which has been expended from time to time during the progress of the work cannot be had without interest. If borrowed, it is secured by interest-bearing notes; and if provided through the sale of bonds, these bonds bear interest. Ordinarily, the interest

charge is based on the assumption that the money expended starts at zero, and mounts uniformly to the total at the end of the construction period. Thus the rate of interest is applied to one-half the total cost, or one-half the rate is applied to the total cost. The construction period varies with different kinds of property, one year, two years, and three years being common lengths of time. It extends to the time when the property is put into operation and begins to earn. A rate of 6 per cent per annum is usually assumed.

The management of a public utility requires a home for its officers and the necessary furniture and fixtures. These may be rented, in which case the rent becomes an operating expense; or the company may own its offices and furniture and the special fixtures needed for its business. The cost then becomes a capital charge. In large properties, street and steam railways particularly, the offices, furniture and fixtures are frequently items of considerable expense. The cost of the equipment of offices, if incurred at the end of the construction period, does not involve interest during the construction period and the item can follow this interest. If, however, it has come earlier, its cost should enter into the sum on which interest during construction is computed.

Certain necessary stores and supplies must be provided ready for use in emergencies before the property can be put into operation. After the plant has been in operation for a time, these gradually adjust themselves as to quantities of the various items. The money represented by stores and supplies can bear no interest unless it be incorporated in the capital, or be carried as a floating debt. In either case the interest on this money becomes a proper charge against earnings. The amount considered is usually an average taken from the books.

Another item which occasions surprise is working capital. By this is meant the money which must always be available to pay bills, labor and the ordinary expenses of operation, and which in the very nature of the fund cannot bear interest except it be incorporated in capital, or be borne as a floating debt with interest paid out of earnings. In either case it becomes a charge against earnings, and therefore takes part as a factor in determining reasonable rates or charges. As between a capital charge and a floating debt it may be pointed out that as a capital charge the rate of interest would presumably be less than as a floating debt. A working capital is as necessary an expense as any other

in the production of a public utility property. Without it the business for which the property was constructed could not be done. How often have we known of the failure of apparently good business enterprises merely for the lack of sufficient working capital. The amount of working capital, like stores and supplies, is usually an average taken from the books.

We have now reached the point at which the property has been completed, having considered items, all of which may enter into the capital investment, and are ready to take up the *second* principal factor, namely, operating expenses. With a working capital to hand, the property has been put into operation. It begins to earn, but a considerable time must elapse ordinarily before the earnings from operation suffice to meet all of the expenditures. By all of the expenditures I mean, interest on the cost of construction, taxes, operating expenses, a fund out of which the expenses of maintaining the integrity of the property can be borne, and another fund to provide for losses of capital at the end of the franchise period. These latter I will discuss separately under the head of "Depreciation" and "Sinking Fund", respectively. During this period of insufficient earnings, money must be borrowed to make up deficits; not only that, but interest must be paid on the borrowed money until the time that the earnings suffice to meet all expenses. This accumulated deficit constitutes what may be termed the cost of procuring a going concern; in other words, the cost of establishing the business. Were the property to change hands at the time the earnings just suffice to pay all expenses, the cost of establishing the business would become the going concern value of the property, and be a part of the total value of the property as a going concern *at that time*. It is a difficult element of cost to determine satisfactorily, in the absence of well-kept accounts, starting with the property itself.

Not infrequently the point is made that the longer it takes to establish the business, that is, the greater the sum of its deficits in earlier years, the greater is its value as a going concern. This apparent inconsistency is explained by the fact that these deficits are real costs, and necessary if the utility is to be had at all. The utility being a necessity, it must be supported by the public the same as any other necessity. The cost of establishing the business therefore becomes a factor in determining reasonable rates or charges. This cost, like that of working capital, if incorporated in the interest-bearing capital, becomes less of a burden against earnings than if carried as a floating debt.

Probably the least understood factor of expense in connection with a public utility property is depreciation. I have called this the *third* factor in determining a reasonable charge for public utility service. By depreciation I mean the money required to to be paid out of earnings in order to meet the expenses of maintaining the integrity of the property. Depreciation is the result of wear and tear and exposure to the elements. It also includes the replacement of machinery which, while not yet worn out, has become obsolete; that is, no longer economical to use; or if still economical, no longer satisfactory to the public. Depreciation includes, further, the wrecking of the machinery due to accident, or to the acts of God.

In the building of a public utility property all of the elements are originally new, but as time goes on these elements suffer wear or decay, some in one degree, some in another. When an element has become worn to a point where it is no longer profitable to keep it in service, it is replaced. Thus in time we have a property which as a whole is made up of old and new elements, the condition of which in the aggregate is something less than the first cost of these elements new. In the very nature of the property it is impossible ever after it is once started to have present in it the full 100 per cent represented by all new elements. It can, however, be maintained in some condition less than 100 per cent, and it is usual and necessary to maintain it at a point which will enable the most satisfactory service to be rendered with the smallest expense consistent with satisfactory service. This point may be anywhere between 80 and 90 per cent, depending on the kind of property.

The expense necessary to keep an element in service during its useful life is a plain operating expense classed under maintenance and repairs, and is not included under depreciation as I am describing it. The depreciation fund is properly a separate fund, maintained as such as distinctly as an interest fund. It is the fund which insures the prolongation of the life of the property indefinitely and always in a condition to render satisfactory service. It is not, however, a fund out of which additions, extensions or betterments may be made, which in their nature constitute additions to capital.

Thus understood, depreciation becomes a factor, and indeed a very important factor in determining reasonable charges for public utility service. Unhappily, the practise of providing this fund is not uniform with the different utilities—not uniform

either in principle or practise. It has long been common for some utilities, railroads for instance, to wear down in lean years and build up in fat years. Thus the condition of the property is not maintained in some uniform condition expressed as a definite percentage of the cost of all new elements, as for example, 80 per cent, but may vary all the way from 75 to 85 per cent.

It is commonly believed by the public that a utility property should not be permitted to earn on more than the so-called present value of its physical elements; that is, their cost new, less depreciation, say 80 per cent of the cost new, or less. As bearing on this I have pointed out that the property, which by means of a proper depreciation fund can be maintained at some definite percentage which enables it to render satisfactory service, has cost 100 per cent. That is, the 80 per cent property can not be had at all without expending the 100 per cent. Thus in order to have an 80 per cent physical condition, we must have a capital charge of 100 per cent. From this it becomes apparent that in determining a resonable charge we must base it not on the percentage which represents condition, but on the cost of the property which cannot be maintained economically above an 80 per cent condition.

If, however, it be insisted that only that percentage of the total cost which is represented by the maintained condition of the property can bear an interest return, the loss of capital and interest thus incurred must be provided for out of earnings in another way, namely, by a sinking fund. This, then, is the *fourth* factor determining a reasonable charge for public utility service. It is to be borne in mind that in this entire discussion I am assuming only actual costs in the capital investment, and only such an interest rate as will induce the investment of the capital in the utility. At the end of the franchise period it is necessary to make good both principal and interest.

The importance of this sinking fund and its magnitude depend on the attitude of the public towards the utility company. The public service corporation works under a franchise, which is simply a grant by the public of the right to do business. With certain kinds of utilities the franchise is perpetual, with others, the life is limited to a definite period, say, 30 years. In some states, Wisconsin for instance, indeterminate franchises are granted; that is, franchises which can be called in, or surrendered, at any time, subject to control by the Railroad Commission of that state. In the case of a limited franchise under which the utility

company must cease operations and close up its business at the end of a definite period, the company must make not only enough to pay the interest on the cost of the plant and maintain it always in condition to render the service demanded by the public, as well as the operating expenses, including taxes, insurance and repairs, but also an additional amount to cover whatever part of the plant must be sacrificed at the end. This means a sinking fund to retire portions of the cost, if not the entire cost. In other words, the company must earn enough during its life to pay back whatever part of the principal has to be sacrificed, as well as the interest on the principal, in addition to maintaining and operating the plant satisfactorily during its franchise life.

This sinking fund is not always, indeed, I may say, is not generally, kept as a separate account, in this country; but is taken out in the form of distributed earnings from year to year in excess of the amount normally required as interest on the cost. Not infrequently what appears as an abnormally large dividend will on analysis be found to be only sufficient in the end to make good to the investor both the interest on his money and the principal sacrificed when the business is closed out.

It should be clear from this that in general a long term franchise is more favorable to the public, so far as charges for service are concerned, than a short term. To illustrate: assume that the plant must be sold for what it will bring as scrap or second-hand material; the difference between its cost and sale value must be made up out of earnings during the life of the franchise. Thus, if the franchise life be short, say 25 years, the sinking fund annuity must be much larger than if the life be 50 years. No annuity is required, when the life is perpetual. No doubt longer term franchises will be granted in the future, particularly now that the control of them is being lodged by the states in public service commissions.

I am not discussing in this paper conditions which have existed in the past, or may exist, now, in connection with old properties, but am confining myself to fundamental things, those which should guide us in our future relations; those relations which will come to exist when the public service corporation is permitted to earn only enough on its investment to bring capital into the field; that is, the critical condition, as it were.

There remains for me only one more topic, and this I have put off until the last, always shying at it, and going around when possible. I refer to discounts and securities. This I have found:

No bond house will even consider financing a public service corporation without a bond discount. I refer particularly to utilities built and operated under a limited franchise. It will have to be a good property to secure better than 15 per cent discount. It is an excellent property which commands as low as 10 per cent discount. The best discount I have ever come across in my own investigations is 8 per cent. This does not apply to municipalities, however, at least not to the same extent.

The simple conclusion is that if the public utility is a necessity and the money for it is obtained in the usual way, one element of cost is the discount on the bonds, which in effect starts the property off with some water in its securities. It is, or is not, water, as you view it. Anyhow it is necessary in the ordinary way of financing properties. Thus we are obliged, in determining a reasonable charge for public utility service, to consider not merely the actual cost as I have previously given it, but something more, namely, the face of the securities which command an interest return. Opinions differ on whether it is better for this discount to be absorbed as a capital charge or carried as an interest charge. So far as the purpose of this paper is concerned it is not material, as in either case there must be a charge against earnings to take care of the discount.

It will be convenient to bring together the several elements which take part in determining a reasonable charge for public utility service. Not all of them take part at the same time, necessarily, for some may appear in one case and not in another; or several may be combined in a single item. In a general way and in a somewhat natural order, they may be summarized as follows:

First, Capital Investment.

1. Preliminary costs covering investigations as to feasibility of project.

NOTE.– Organization, promotion, administration, and legal expenses, engineering and superintendence during construction, which are distributed over the whole period of construction, are more conveniently placed later in the schedule.

2. The physical property; the several items making up the whole arranged in order, each affected with its proper allowances to cover contingencies, special engineering, and other costs peculiar to the item; land first, followed by clearing and grubbing, then the various structures and equipment; sub-contractors' profits included with separate items.

3. General contingencies applicable to the property as a whole as distinguished from special contingencies applicable to particular items.
4. General contractor's profits; or, the profits to an engineering firm building the property on the "cost plus a percentage" plan.
5. General engineering, and superintendence during construction.
6. Insurance and taxes.
7. Organization, administration, and legal expenses.
8. Cost of promotion, and promoter's profits.
9. Interest during the construction period.
10. Office furniture and fixtures.
11. Stores and supplies.
12. Working capital.

Second, Operating Expenses.

13. Operating expenses *per se*; that is, salaries, wages, fuel and other supplies, repairs and upkeep; all expenditures required in rendering the service of the utility, including insurance and taxes.
14. Interest on the capital investment (the actual cost of the property), *i.e.*, interest on securities which must be paid regularly.
15. Interest on floating debts; this may include the discount on bonds, and the cost of financing, if these have not been incorporated with capital.
16. Cost of establishing the business; the sums of money required to be borrowed, with interest on the same, to make good the differences between the earnings and expenditures up to the time the earnings become sufficient to meet all expenditures. This may be made a capital charge, or carried as a floating debt to be paid out of future earnings.

Third, Depreciation Fund.

17. The regular contribution to the depreciation fund, out of which the integrity of the property is to be maintained.

Fourth, Sinking Fund.

18. The annuity required to retire such portions of the securities as may be necessary at the expiration of the franchise life of the property, in order that the investor may receive back his entire principal when the business is closed out.

It will surprise everyone not familiar with the cost of building utility plants to learn that the so-called over-head charges are in the aggregate a large percentage of the costs of labor and the material things entering into their construction. An examination of the various percentages mentioned in discussing the elements of cost, omitting items 1, 4, 8, 15 and 16, will disclose that if the individual contingencies of construction, special engineering charges, and contractor's profits be assumed to be embraced in item 2, the total percentage may vary from 12 to 25 per cent; and if these inside percentages be added to the outside, or general, percentages, the total percentage may vary from 30 to 60 per cent.

It is to be regretted that engineers, and others who have had experience in building properties, and valuing them afterwards, have not done more towards disseminating knowledge of the actual conditions found in such work. We should then be much further along towards the mutual understanding which must exist before the public and the public service corporation can get together on common ground. But engineers have many times hesitated to use the larger percentages, fearing to be accused of favoring the corporation. They have preferred instead to secure the equivalent of them by using larger units of costs; or have used the smaller percentages, influenced by the feeling, unconsciously perhaps, that all things considered, the results were fair enough. In combining the judicial with their engineering function, they have unwittingly only obscured the issue. All too frequently engineers have felt obliged to exert themselves to the utmost in favor of their client, leaving the interests of the other side to be fought for with equal solicitude by an opposing engineer. Thus they have become advocates. This, in my opinion, is not the best way to handle these momentous problems. It would be far better in these troublesome times to throw open the blinds and let in all the light, our motto being *veritas vincat.*

A paper presented at the 289th meeting of the American Institute of Electrical Engineers, New York, December 12, 1913.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

BY F. M. FARMER

INTRODUCTION

The object of this paper is to record the results of an investigation which has been made at the Electrical Testing Laboratories to determine the effect of electrode area on the apparent dielectric strength of insulating materials in the form of thin sheets.

It is well known that many conditions affect the results when testing such sheet insulating materials as varnished cambric for dielectric strength. The principal ones are temperature, rate of application of the potential, shape of the electrodes and size of the electrodes. Unfortunately there are, as yet, no standard specifications for testing these materials and each manufacturer, purchaser and testing laboratory uses those methods which seem to be the most satisfactory. In general, varnished cambric and similar materials are tested by placing the sample between, and in contact with, two similar flat circular electrodes to which the potential is applied. The greatest divergence appears to be in the size of the electrodes which vary from needle points to disks 15 in. (38 cm.) in diameter.

The argument advanced in favor of the use of large electrodes is that there is more or less variation in the material, and that the minimum value of the dielectric strength will be found more readily with large electrodes than with small ones. On the other hand, it is contended that the use of very small electrodes introduces an abnormal condition causing concentration of the electrical stress and failure at too low potentials. While much work has been done in investigations of the dielectric

strength of insulating materials, especially air, no data have been published (so far as the writer knows) showing just what effect may be expected with variation in the size of the electrodes, and it is thought, therefore, that the results of some work done in this particular direction will be of interest.

The following tests were made with two, similar, flat, circular electrodes ranging from 1/64 to 6, 10, and 15 in. (0.39 mm. to 15.2, 25.4 and 38 cm.) in diameter and placed directly opposite each other;

1. On insulating cloth and thin sheet hard rubber in air.
2. On insulating cloth in air and in transformer oil.
3. On transformer oil with various spacings.
4. On air with various spacings.

Too many variables enter in tests of this kind to permit a high degree of precision. It is only by taking the average of a relatively large number of readings that even an approximately reliable result can be obtained. However, in these tests, the object was to obtain relative results only, consequently the data should be considered as qualitative rather than quantitative.

Apparatus

Most of the tests were made with a 10-kv-a. transformer connected to a 62.5-cycle, 150-kv-a. generator, but a few of the tests in air were made with two 2-kv-a. transformers. The high-tension voltage was controlled, in all cases, with a variable ratio auto-transformer in the low-tension circuit and measured with a voltmeter connected across the low-tension terminals. Check measurements were made at intervals with an electrostatic voltmeter directly across the high-tension terminals but in no case was any appreciable discrepancy found. Oscillograph records showed that the wave form was practically a sine curve under all conditions prevailing during the tests. The potential was always applied at a very low value (practically zero) and raised gradually and smoothly at a rate of about 1000 to 1200 volts per second. Enough tests (rarely less than ten) were made under each condition to insure an average value of reasonable reliability. The electrodes, which were $\frac{3}{8}$ in. (9.5 mm.) in diameter and over, were flat brass disks 1/16 to 3/16 in. (1.5 to 4.7 mm.) thick with the corners slightly rounded. The electrodes $\frac{1}{4}$ in. in diameter and less, consisted of $\frac{1}{4}$-in. (6.3 mm.) brass rods tapered to the required area at the ends, the corners being slightly rounded.

In all tests on cloth and hard rubber, except those with electrodes over 6 in. (15.2 cm.) in diameter, the electrodes were arranged similar to an ordinary spark gap, being attached to the ends of horizontal rods which were supported by suitable vertical pillars. The specimen was placed between the electrodes which were then brought together with sufficient pressure to insure uniform and complete contact. The pressure was probably never more than a few ounces. Previous tests have

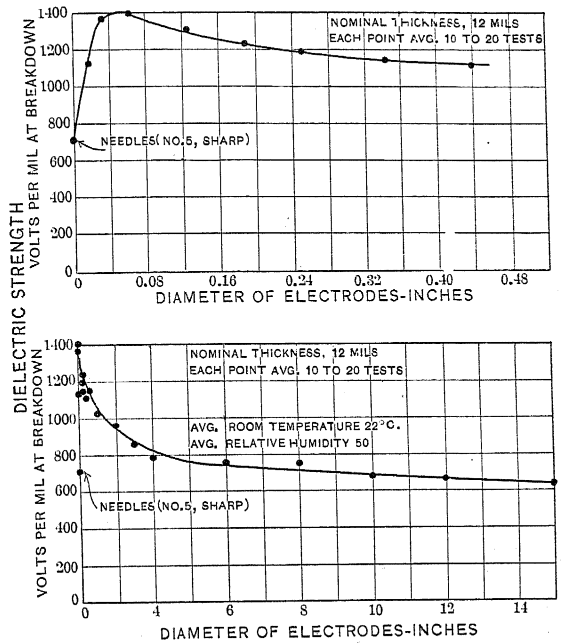

FIG. 1—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WHEN TESTED IN AIR.

shown that wide variations in pressures of this order had no appreciable effect.

TESTS ON INSULATING CLOTH AND HARD RUBBER IN AIR

The results of the tests on varnished cambric (nominally 12 mils thick) are given in Table I and Fig. 1. The lower curve shows that the apparent dielectric strength decreases very rapidly from a maximum value as the size of the electrodes is increased, but that the decrease is relatively slow beyond about

5 in. (12.7 cm.) diameter. The total decrease from the maximum of 1390 volts per mil with 1/16-in. (1.5-mm.) electrodes to 625 volts with 15-in. (38-cm.) electrodes is about 55 per cent of which about 42 per cent took place between the 1/16 in. (1.5 mm.) and 4-in. (10.16-cm.) electrodes.

TABLE I.

VARIATION IN DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WITH VARIATION IN ELECTRODE AREA. ALL TESTS IN AIR.

Size of electrodes		No. of punctures	Average thickness, mils.	Volts per mil at puncture		
Diameter inches	Area sq. in.			Max.	Min.	Avg.
Needles	—	12	12.6	960	505	720
0.0156 (1/64)	0.0002	13	12.4	1195	1000	1135
0.0312 (1/32)	0.0008	18	12.7	1430	1260	1370
0.0625 (1/16)	0.0030	15	12.9	1465	1330	1390
0.125 (1/8)	0.012;	15	12.9	1395	1130	1305
0.1875 (3/16)	0.0276	14	12.4	1330	1135	1235
0.25 (1/4)	0.0490	21	13.4	1320	905	1195
0.344 (11/32)	0.0928	10	13.1	1185	1020	1135
0.438 (7/16)	0.150	14	13.1	1225	1000	1115
0.5 (1/2)	0.196	15	13.1	1240	930	1150
1	0.785	15	12.9	1225	910	1030
2	3.14	10	13.4	1030	890	970
3	7.07	10	12.8	1005	665	870
4	12.6	10	11.9	960	615	790
6	28.3	10	12.3	850	690	755
8	50.3	10	12.8	875	685	755
10	78.5	10	12.8	915	550	680
12	113	10	13.0	745	560	665
15	177	10	12.4	685	530	625

NOTE:—Fresh material used in each test.

The upper curve in Fig. 1 is the first part of the lower curve plotted on a larger scale. This shows that a maximum value is obtained with electrodes about 1/16 in. (1.5 mm.) diameter, lower values being obtained with smaller electrodes as well as with larger electrodes. The results with needles (No. 5, Sharp) are about the same as those obtained with the very large electrodes.

Table II and Fig. 2 show the results of similar tests on sheet hard rubber of 7-, 9-, and 12-in. (17.7-, 22.8- and 30.4-cm.) nominal thickness respectively. These tests were not as extensive as those made on the cloth but the curves have the same general shape although the effect of increasing the size of the electrodes is much less marked.

TABLE II.

VARIATION IN DIELECTRIC STRENGTH OF SHEET HARD RUBBER WITH VARIATION IN ELECTRODE AREA. ALL TESTS IN AIR.

Size of electrodes		No. of punctures	Average thickness, mils	Volts per mil at puncture		
Diameter inches	Area sq. in.			Max.	Min.	Avg.
(a) Nominal Thickness, 9 mils.						
Needles	—	11	9.0	1970	1275	1705
0.0156 (1/64)	0.0002	13	8.9	2135	1745	1950
0.0312 (1/32)	0.0008	10	8.8	2095	1710	1970
0.0625 (1/16)	0.0030	13	8.8	2100	1600	1865
0.125 (1/8)	0.0123	15	9.0	2105	1075	1790
0.1875 (3/16)	0.0276	14	8.9	2110	1365	1855
0.25 (1/4)	0.0490	15	8.9	2130	1610	1900
0.344 (11/32)	0.0928	24	8.8	2065	1410	1795
0.5 (1/2)	0.196	16	9.0	1945	1510	1800
1	0.785	9	8.8	2045	1570	1860
2	3.14	11	8.8	1820	1600	1720
3	7.07	10	8.8	1715	1330	1530
4	12.6	8	8.8	1570	1245	1410
6	28.3	10	8.8	1300	885	1180
10	78.5	10	8.8	1875	550	1055
(b) Nominal Thickness, 7 mils.						
0.0625 (1/16)	0.0030	10	7.3	2000	1730	1865
0.5 (1/2)	0.196	10	7.3	1965	1770	1825
1	0.785	10	7.6	1755	1630	1700
2	3.14	10	7.6	1725	1500	1630
4	12.6	10	7.6	1600	1375	1515
6	28.3	10	7.2	1180	875	1060
(c) Nominal Thickness, 12 mils.						
0.0625 (1/16)	0.0030	10	12.3	1545	1400	1505
0.5 (1/2)	0.196	10	11.7	1620	1185	1460
1	0.785	10	11.7	1600	1225	1425
2	3.14	10	12.3	1365	1230	1300
4	12.6	10	12.3	1380	1200	1235
6	28.3	10	11.7	1165	955	1015

NOTE:—Fresh material used in each test.

The usual explanation for the lower dielectric strength obtained with the large electrodes is that more "weak spots" are included as the area is increased, thus decreasing the average puncture voltage. This explanation would, at first glance, seem to be entirely reasonable for it is well known that in most insulating cloths the insulating material does not penetrate the threads deeply but merely forms a film on the surface of the cloth and, as the threads vary in thickness, the dielectric strength of the points where the threads cross each other will depend upon the thickness of the threads. Where the threads are thick, the

insulating material will be thin, and vice-versa. Similarly, minute variations in the composition of hard rubber might be expected to make "weak spots" when the material is in very thin sheets. It would seem therefore that the greater the electrode area, the greater will be the variation in the weak spots included, until an area is reached such that the weakest spot is always included. Beyond this point the breakdown voltage would therefore remain substantially constant.

On the other hand, as the electrode area is decreased below

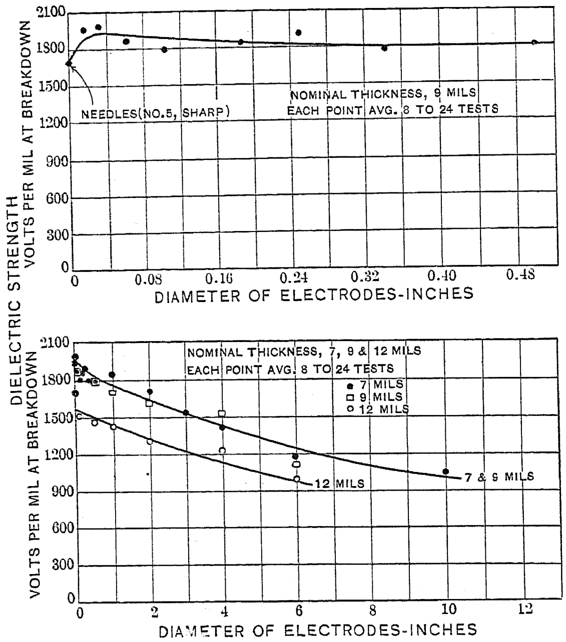

FIG 2.—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF THIN SHEET HARD RUBBER WHEN TESTED IN AIR.

this particular value, one would expect that *occasionally* at least, one of the weakest spots would be included under a given size electrode. An examination of the column of minima in the tables does not show any such result. The figures vary in the same more or less regular manner as do the figures for the average. Furthermore, this explanation does not account for the results obtained with very small electrodes where the most marked effect is found. With such electrodes, it is probable that the air adjacent to the points is broken down long before punc-

ture occurs. This should result in the effective area being increased so that when puncture occurs, this area would be practically the same for all of the very small electrodes. Consequently, according to the weak spot theory, no material variation in the dielectric strength should result with electrodes less than about $\frac{1}{4}$ in. (6.3 mm.) diameter.

It is apparent from the above that the effect of variation in electrode area is not wholly due to variations in the material. With the smaller electrodes at least, it would appear to be due to the change in the distribution of the electrical stress. As the distribution of the stress in the medium surrounding the electrode terminals would be affected by the nature of that medium, some tests were made in moist air and in oil.

Tests on Varnished Cambric in Moist Air

The first tests were made in a box in which the relative humidity could be kept at practically 100 per cent. Considerable difficulty was experienced in getting results which could be duplicated. The following data are fairly representative:

Diameter of electrodes, inches	Volts per mil at breakdown
1/32	1000
1/2	1010
1	1000
3	975

Relative humidity 98 per cent. Temperature 21 deg. cent.

These figures appeared to indicate that with very moist air, the effect found in the first tests does not occur. This is probably due however to the presence of moisture films on the surfaces of the cloth which make the effective area the same for all of the smaller electrodes.

Shortly after the above tests were made, an opportunity occurred to make some tests under practically outdoor conditions on a very foggy day when the relative humidity averaged 90 to 100 per cent. The results of these tests are as follows:

Diameter of electrodes inches	Volts per mil at breakdown
1/32	1170
3/8	1200
1	1200
3	1060
6	950

Relative humidity 90–100 per cent. Temperature 10 deg. cent, (approx.).

These results do not check with those made in the box, although the variation is much less than in Fig. 1, especially with the smaller electrodes. The lack of agreement with the box test may have been due to the fact that the latter tests were made in a draft in an open doorway while the former were made in a box in which the air was perfectly still and where a film of moisture could probably form more readily.

Tests on Varnished Cambric under Oil

The following tests were made on two kinds of insulating cloth with various sizes of electrodes:

(*a*) In air.

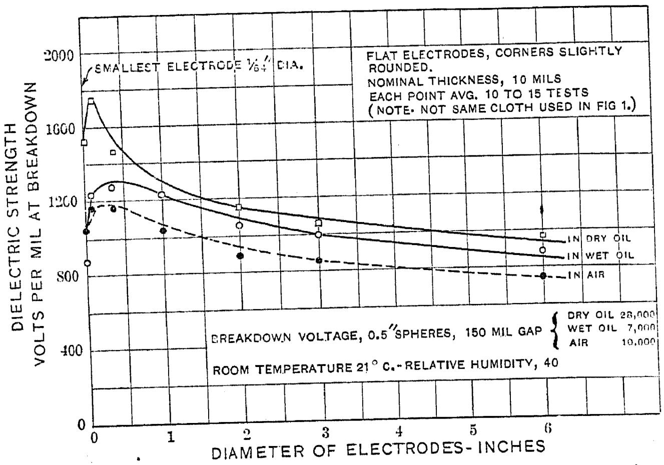

Fig. 3—Varnished Cambric——Effect of Electrode Area on Apparent Dielectric Strength in Air and in Oil.

(*b*) Under moisture-laden oil having a breakdown value between ½-in. (12.7-mm.) spheres, 150 mils apart, of 7000 volts. This test was made on only one kind of cloth.

(*c*) Under untreated oil having a breakdown value of 28,000 volts in one case and 20,000 volts in the other.

The results of these tests are shown in Figs. 3 and 4. It will be noted that, as found in the previous tests, the dielectric strength increases when the electrode diameter is decreased and that it is uniformly greater when the cloth is surrounded with oil than when surrounded with air. It is also to be noted that with very small electrodes the effect of variation in the diameter is apparently somewhat greater with oil than with air.

Further tests were then made with oil and with air as the dielectric to determine whether they would show the same characteristic curve as the solid dielectrics. Since it was a relatively easy matter to change the thickness of the " dielectric " in these tests, curves were taken with various spacings of the electrodes.

Tests with Oil as the Dielectric

The oil used in these tests was a " water-white " oil, taken directly from the barrel and strained through a double layer of fine silk cloth. It had a puncture value between 0.5-in. (32.7-mm.) spheres spaced 150 mils apart of 35,000 volts.

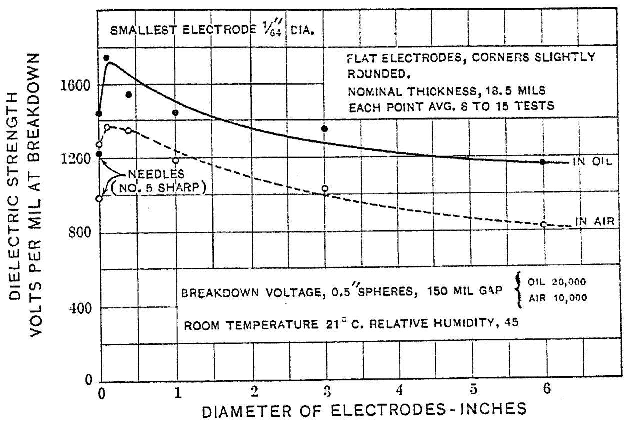

Fig. 4—Black Varnished Cloth—Effect of Electrode Area on Apparent Dielectric Strength in Air and in Oil.

Tests were made with 1/64-, 3/32-, $\frac{3}{8}$-, 1-, 3-, and 6-in. (0.3-, 2.3-, 9.5-mm. and 2.5-, 7.6-, 15.2-cm.) electrodes and with spacings of 10, 20, 40, 70,100, 200, 400, and 750 mils.

The results are shown in Fig. 5, from which the following deductions can be made:

(*a*) The dielectric strength increases as the diameter of the electrodes is decreased, *when a thin layer of the dielectric is used,* as strikingly shown by the heavy solid curve which is for 10-mil spacing. This confirms the general result shown in Fig. 1. The effect is, however, much more marked and it is largely confined to the electrodes less than 0.5 in. (12.7 mm.) diameter.

(*b*) The effect of change in electrode diameter decreases as the electrodes are separated, the dielectric strength with the

smaller electrodes becoming smaller and that with the larger electrodes becoming greater. The effect practically disappears at a separation of 400 mils, where the dielectric strength is about 100 to 150 volts per mil irrespective of the size of the electrodes.

(*c*) It is generally known that the dielectric strength of a material is not proportional to the thickness, and that with thin layers especially, the strength increases rapidly as the thickness is decreased. Fig. 5 shows that with 1/64-in. (0.3-mm.) electrodes, the dielectric strength varies from about 90 volts per mil with a spacing or thickness of dielectric of 750 mils to about 900 volts per mil with a spacing of 10 mils. But as the

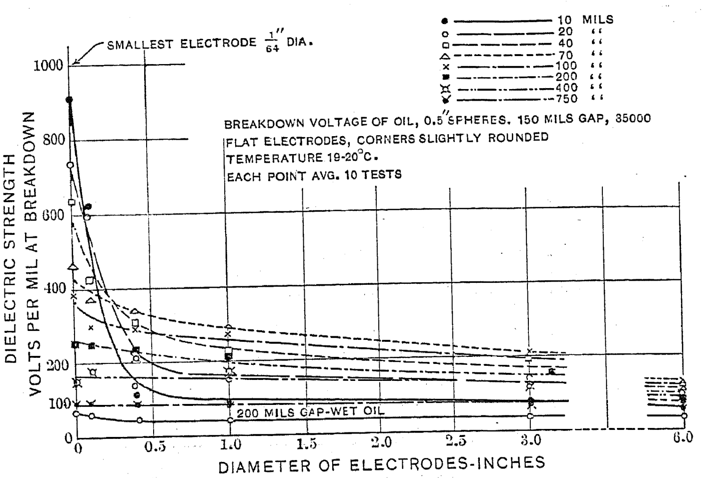

Fig. 5—Effect of Electrode Area on Apparent Dielectric Strength of Oils with Various Gaps.

electrode diameters are increased, the dielectric strength becomes more independent of the thickness. At 6 in. (15.2 cm.) diameter, the dielectric strength is practically the same for all thicknesses from 10 mils to 750 mils.

Tests with Air as the Dielectric

These tests were made under ordinary atmospheric conditions and, as only approximate relative data were wanted, no special precautions were taken. The electrodes were simply cleaned by wiping with cloth or filter paper and no attempt was made to have them chemically clean.

The results are indicated in Fig. 6, in which the following will be noted;

(a) As in all previous tests, the electrode area has a marked influence *when the dielectric is thin*.

(b) There appears to be a certain thickness of air (about 100 mils) where the electrode diameter has no effect. With smaller separations, the dielectric strength increases as the electrodes become smaller, and with greater separations the dielectric strength decreases.

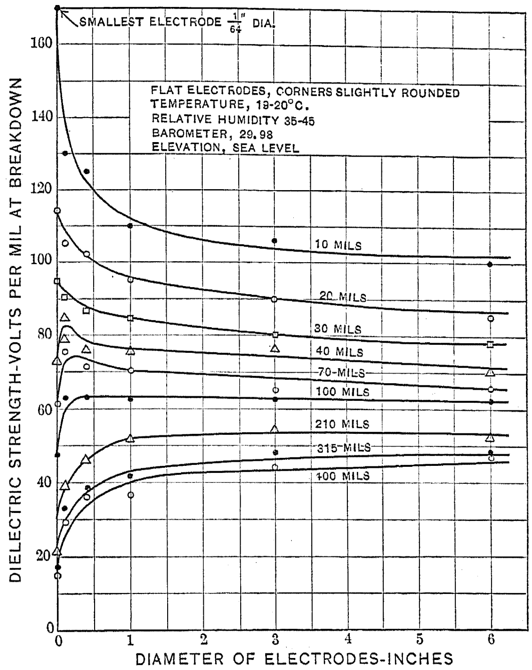

FIG. 6—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF AIR WITH VARIOUS GAPS.

(c) The dielectric strength is higher for thin layers than for thick ones, a characteristic which has been found by many experimenters. Unlike oil, however, the dielectric strength varies inversely with the separation for all sizes of electrodes, but the variation is much greater for the small electrodes.

ADDITIONAL TESTS WITH SOLID DIELECTRIC

The results of the tests in oil and air having indicated that, in those cases, the effect of variation in electrode diameter

occurs only with very thin layers, a few additional tests were made on hard rubber of various thicknesses. These tests were made in oil.

Not enough time or material was available to make these

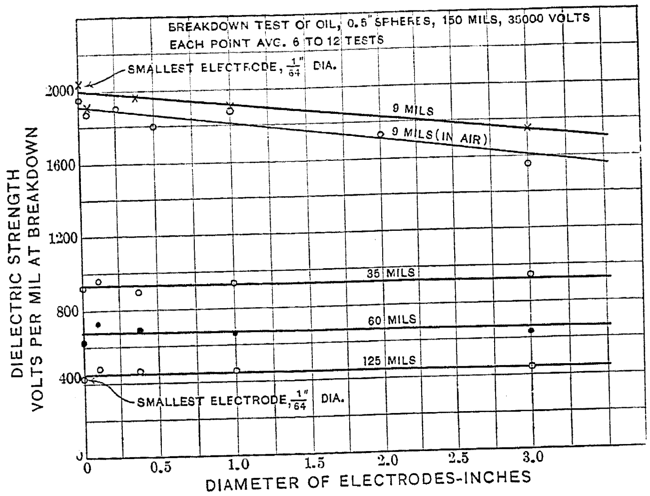

FIG. 7—HARD RUBBER IN OIL—EFFECT OF ELECTRODE AREAS WITH VARIOUS THICKNESSES.

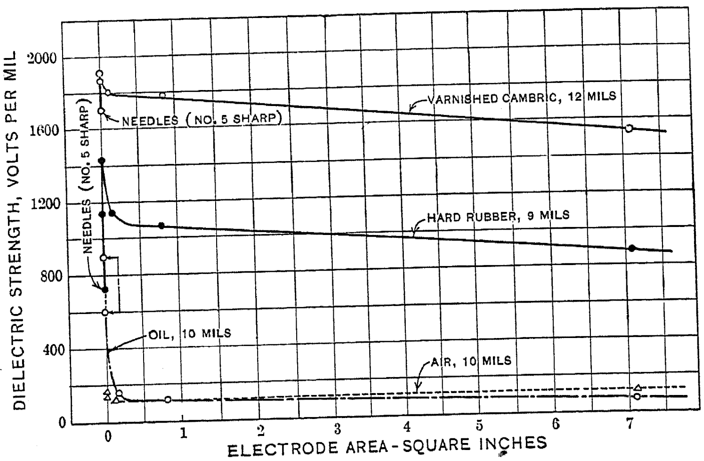

FIG. 8—DIELECTRIC STRENGTH VS. ELECTRODE AREA IN SQUARE INCHES

tests as complete as would be desirable, but the results, as shown in Fig. 7, appear to confirm, in a less marked degree, those found for oil and air. That is, this variation with electrode area is found only with thin dielectrics.

Fig. 8 shows the results for thin sheets of cambric, hard rubber, oil and air, respectively, plotted on an electrode area basis instead of a diameter basis.

Conclusions

In work of this kind, so many variables enter that a high degree of reliability can not be expected. Although the results given are averages of a great many determinations, it is felt that considerable allowance must be made in drawing final conclusions. Furthermore, a great deal more work is necessary, such as an investigation of other classes of insulators, effect with electrodes of various forms, effect of other surrounding media including solids, et cetera. However, so far as the original purpose of these tests is concerned, viz., the effect of the variation of the electrode area on the apparent dielectric strength of thin insulations, the following conclusions may be drawn from the results:

1. The apparent dielectric strength of insulating materials in *thin* sheet form is materially higher with small electrodes than with large ones. This probably applies generally to all dielectrics, gaseous, liquid and solid, although the magnitude and the law of the variation differs widely with different materials. The variation with ordinary sheet insulating materials, such as paper and cloth, may be 40 or 50 per cent between 1/64 in. and 8 or 10 in. (0.3 mm. and 20.3 or 25.4 cm.) diameter, while with oil, under the same conditions, the variation is over one thousand per cent.

2. The prevalent opinion is that the electrostatic stress is concentrated when the dielectric is between sharp points and that failure will occur at a low value. This appears to be the case when the points are very sharp, such as needle points, but as soon as they have an appreciable area, the puncture value is much higher than with large electrodes.

3. The apparent dielectric strength of thin layers of solid dielectrics may vary markedly with the nature of the surrounding medium, being in general, apparently, higher in oil than in air.

4. These tests emphasize a need which has been frequently pointed out in the PROCEEDINGS of the Institute, viz., standard specifications for the testing of insulating materials, especially when in the form of thin sheets. It does not seem probable

that the dielectric strength of an insulating material under all working conditions can ever be predicted with exactness, but at least we can have standard methods of rating such materials so that a value for the dielectric strength will have the same significance to the manufacturer, the purchaser and the designing engineer.

DISCUSSION ON "THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS" (FARMER), NEW YORK, DECEMBER 12, 1913.

F. W. Peek, Jr.: Three types of insulation are in general use—gaseous, liquid and solid. The mechanism of breakdown differs in many respects in the three types. Any insulation, under given conditions, ruptures at a given point when the dielectric flux density at that point exceeds some definite value. The total dielectric flux depends upon the capacity and the electromotive force; that is, upon the size and spacing of conductors and the voltage between them. The flux density at various points will also be different, depending upon the configuration of electrode. The flux density at any point is proportional to the gradient at that point. The strength of insulation, therefore, may also be expressed in terms of the *gradient measured at the point where rupture occurs.* The voltage required to rupture insulation, divided by its thickness, is not a measure of the insulation strength. It is the average gradient. The maximum gradient where rupture starts is much higher. For instance, take two pairs of spheres, one pair a half-centimeter in diameter, spaced one cm. apart, and the other pair two cm. in diameter, spaced one cm. apart. Apply a voltage of 100 kv. across pair No. 1. The gradient is maximum at the surface and is by calculation $\frac{de}{dx} = 270 \frac{\text{kv.}}{\text{cm.}}$. The average gradient $\frac{e}{x} = \frac{100 \text{ kv.}}{1 \text{ cm.}}$. One pair No. 2, 100 kilovolts gives

$$\frac{de}{dx} = 135 \frac{\text{kv.}}{\text{cm.}}; \frac{e}{x} = 100 \frac{\text{kv.}}{\text{cm.}}$$

Thus for the same voltage and spacing the actual stress is quite different, depending upon the curvature.

If 20-cm. spheres are taken, under the above conditions $\frac{de}{dx} = 103$ and $\frac{e}{x} = 100$. Thus with large radius the average gradients and $\frac{de}{dx}$ are approximately equal. This is the reason that in any investigation (other than commercial testing) made to determine the strength of insulation, some electrode is taken in which the dielectric flux density and gradient at various points can be calculated—that is, spheres, parallel wires, or a wire in a cylinder. These may be arranged so that the break is local, as corona in air on two parallel wires at large spacings. The break starts at the surface because the flux density is a maximum there. The conducting corona extends out approximately to a point where the flux density is below the breakdown density. Only when the surfaces are close

together does a complete spark-over take place before corona forms.

Let us now consider briefly the mechanism of breakdown of three types of insulation.

Air. Air has a greater apparent strength around small conductors than large ones, as for instance, sphere or wires. The explanation apparently is that air has a constant strength of $30 \frac{\text{kv.}}{\text{cm.}}$; rupture, however, does not occur when this gradient is reached at the conductor surface, but only when this gradient is reached at a finite distance from the conductor and when the gradient at the surface is therefore higher. Energy is necessary to rupture insulation. The rupturing energy is stored in this space between the conductor surface where the gradient is high and a finite distance away where the gradient is 30 kv./cm. This distance may be called the energy storage distance, or it may be considered as the distance required to reach ionic saturation by successive collisions between the conductor surface and where the gradient is $30 \frac{\text{kv.}}{\text{cm.}}$, the "accelerating distance."

This distance is $0.301 \sqrt{r}$ cm. for wires, and $0.27 \sqrt{R}$ cm. for spheres. If the conductors are placed closer together than the free energy storage or accelerating distance the apparent strength increases in order that sufficient energy may be stored in the limited space.[1] Although the real strength of air, or the gradient required to bring the ions up to sufficient velocity to produce other ions by collision, is 30 kv. per cm. between parallel planes, with limited energy distance, that is, thin films, gradients as high as $250 \frac{\text{kv.}}{\text{cm.}}$ are required to cause rupture. There is very little loss in air until after rupture, as brush discharge or corona, occurs. For this reason air may be stressed to within a few per cent of breakdown voltage without loss and consequent heating and weakening. Air is uniform and homogeneous and therefore free from "weak spots." The curves given in Fig. 6 of Mr. Farmer's paper are, on account of the characteristics stated above, exactly what would be expected. The ordinate does not represent the dielectric strength, but $\frac{e}{x}$, the average gradient of rupture. The dielectric strength would be represented by $\frac{de}{dx}$. Take for example the curve at

1. This is fully discussed in the following papers by F. W. Peek, Jr.: *The Law of Corona and the Dielectric Strength of Air-I*, TRANS. A.I.E.E. 1911, Vol. XXX, p. 1889; *The Law of Corona-II*, TRANS. A.I.E.E. 1912 Vol. XXXI, p. 1051; *The Law of Corona-III*, TRANS. A.I.E.E., this volume, and "High-Voltage Engineering," in the *Journal* of the Franklin Institute, December, 1913, (No. 1056) page 611.

210-mil spacing. Fig. 1 of this discussion gives curves plotted from data taken from *The Law of Corona-III*, for 0.508-cm. (200-mil) spacing between spheres. Plotted with $\frac{e}{x}$ this gives a curve exactly similar to Mr. Farmer's in Fig. 6. Plotted with $\frac{de}{dx}$, the actual gradient at the surface where breakdown occurs, the curve increases with decreasing diameter of sphere, due to the varying energy distance with varying diameter of sphere. As the radius of the spheres increases, the average gradient curve $\frac{e}{x}$ and the surface gradient curve $\frac{de}{dx}$ come together, because as the radius becomes large compared with the spacing, the flux becomes more nearly uniform.

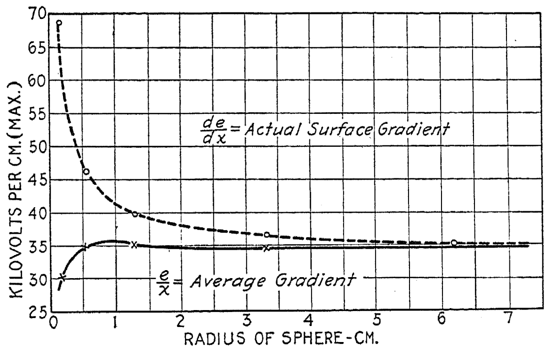

FIG. 1—SPARK-OVER OF SPHERES IN AIR. SPACING = 5.08 CM. (200 MILS.)

Oil. The mechanism of breakdown of pure oil is very similar to that of air and follows the same laws.[2] The constants are, however, different. The energy distance and therefore the apparent strength is much higher. With limited energy distance, strengths as high as a million volts per cm. have been reached with electrodes which gave an apparent strength of 100 $\frac{\text{kv.}}{\text{cm.}}$ when the energy distance was not limited.

Solid Insulation. Like air and oil, solid insulations require energy to cause rupture and therefore have a greater apparent strength for small conductors and for small spacings or thin films. If the curves in Fig. 1 in Mr. Farmer's paper were plotted with the true gradient $\frac{de}{dx}$ where rupture starts, and not $\frac{e}{x}$,

2. "High-Voltage Engineering," Franklin Institute *Journal*, loc. cit.

the gradient would increase with decreasing electrode and not show the maximum hump. The curve as plotted does not express the dielectric strength. If this curve were taken at a larger spacing and plotted with $\frac{e}{x}$ the hump would occur at a larger size of electrode. There are conditions where the hump, due to varying energy distance with radius, might actually occur when plotted with the actual gradient. This curve is also affected by the "weak spots", otherwise the curve would be parallel to the axis when the "flat disks" are used. These disks have about equal curvature on the edge, and thus equal effect due to flux concentration. $\frac{e}{x}$ may then be used for comparing strength. This part of the curve practically follows the probability curve.

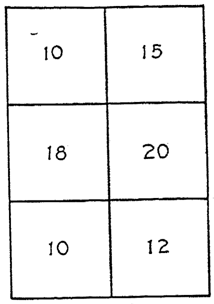

FIG. 2

For example, suppose Fig. 2 herewith, represents a piece of solid insulation one mil thick and *sufficiently large to cover every condition of "weak spot"*. Divide this into six equal squares, each of area a. The strength is marked on the various areas. Assume that an electrode giving no edge effect is used. With electrode of area a, six tests are required to go over the whole piece. With electrodes of area $2a$ three tests are required, with area $3a$ two tests, and with area $6a$ only one test. The following results may be obtained:

Area of electrode	No. of punctures	Total area covered	Volts per mil		
			max.	min.	average
a	6	6a	20	10	14
2a	3	6a	18	10	13
3a	2	6a	12	10	11
6a	1	6a	10	10	10

The results are somewhat similar to the lower points of the curve in Mr. Farmer's paper. By the method described in the paper, however, the same number of punctures is taken for each size of electrode. Thus for the large electrodes much more insulation is tested than for the small electrodes, and the minimum should therefore be much lower for the large electrodes. In the example I have given, the number of tests is taken so that the total area covered is the same for all electrodes. Thus where edge effect exists it would be more rational to make the circumference covered equal.

With laminated insulation, as in cables, this effect of weak spots should not be so great, as they are not likely to line up in the separate layers.

The curves obtained are therefore probability curves modified by flux distribution (because they are not plotted in terms of maximum flux density), and energy distance.

While loss in air and pure oil is a phenomenon after breakdown occurs, in solid insulation loss occurs as soon as voltage is applied. This heats the insulation and weakens it. It is for this reason generally impossible to hold more than 25 per cent of the "instantaneous" puncture voltage indefinitely. For instance, on a given insulation, if the voltage is brought up rapidly or "instantaneously" 100 kv. may be required to cause rupture; 75 kv. may be applied for one minute before rupture occurs; 50 kv. may be applied for four minutes, and 30 kv. indefinitely. Very high voltages of steep wave front, or of exceedingly short duration, may be applied without apparent effect, but which, upon a number of applications, cause puncture.

The mechanism of breakdown in solid insulation is quite complicated and greatly affected by occluded air and moisture. If a local breakdown occurs, local charring takes place. This concentrates the flux and the break is extended by steps indefinitely. Breakdown often occurs in this way by a concentration of the flux, independent of true dielectric strength, as the result of moisture, which places extra stress at local points.

Although with flat plates the exact gradient cannot be calculated, they are sufficient for most practical purposes in commercial test. The radius of the plate and also of the edge should be specified. The test should also, probably, be made under oil. The method of applying voltage should be specified, as well as material and weight of disk, and method of drying material, etc. A great deal depends upon radiation and heat conduction. After all, the "instantaneous" breakdown tests, just discussed, are of little commerical use unless an endurance test is added—that is, as is generally done, by starting at a given percentage of the instantaneous voltage and increasing by a given percentage at given time intervals until puncture occurs. We will be greatly helped in commercial testing when means of measuring small energy losses are simplified and perfected. In this way the presence of moisture is quickly shown.

Phillips Thomas: Mr. Farmer's paper brings out many points and adds one more link to the chain of evidence, showing the necessity, when giving figures for dielectric strength, of including pretty exact information on the method used in making the tests.

The results at which he has arrived agree in general with those found by the writer and by others for electrode diameters up to ½ in. (12.7 mm.).

As stated in this paper, the law of probability does not seem to apply below ¼ in. (6.35 mm.) diameter of electrodes, and from the nature of the material tested it seems certain that the limiting size of electrode which would always cover the weakest

spot will occur long before 15 in. (38 cm.) is reached. Since the charging current through the dielectric at a given voltage varies inversely as the dielectric thickness and varies directly as the electrode area, any distortion due to this current will react directly on the values found.

In testing various sizes of condensers for breakdown strength, we use an outfit very similar to that described in this paper and have found it necessary to parallel the tested condenser with one of much larger capacity so that the distortion and regulation at a given voltage will not depend upon the capacity of the piece being tested. We have been forced also to measure the breakdown voltage directly at the electrodes, in order to reach comparative results.

The paper states that the voltage reading was checked at intervals by connecting an electrostatic voltmeter directly across the high-tension terminals. Such a check will detect any capacity regulation if made while the test piece is connected, but will not give any information as to distortion. This distortion and regulation will be different for each area and thickness tested and is certain to give misleading results, unless either its presence or its effect is eliminated in some way.

R. P. Jackson: This paper by Mr. Farmer gives some data that are in a way quite surprising and show strongly the importance of having standardized methods of testing insulation materials.

In general, it is my opinion that the lower valued results obtained by Mr. Farmer come nearer the truth in the form in which it is desirable to know it, for the reason that the large area electrodes more nearly duplicate the conditions under which insulation operates and is subject to stress. For that reason the lower valued results obtained with the large area disks apparently give a better guide for the use of the material, and at least as good a guide as to the quality of various grades of similar material.

Different explanations can be offered as to why the results vary so much with the different sizes of electrodes, and the time not being sufficient to duplicate any of the tests, one cannot more than conjecture as to the actual cause of the variation. Varying sizes of electrodes with very thin insulation will, of course, vary the static capacity of the test, and if the supply transformer is small, may cause a rise of voltage at least when the supplied voltage is near its maximum value and the insulation under greatest stress. The condition of capacity and corona or static fringe around the electrodes is liable to cause surges and oscillations which would tend to produce puncture at lower apparent values. Thin air pockets between the electrodes and the insulating material also become sources of corona and therefore heat which might vary with the size of electrodes, especially if the insulating material and the electrodes were not exact plane surfaces and sufficient pressure were not brought to bear to bring

the two surfaces into contact. Another source of variation has been betrayed by similar tests in which thin material failed when the electrodes were of tinfoil of considerable area, and failed at a much lower value than when the electrodes were of small area and of brass pieces of considerable mass. Such tests, however, were of some little duration and the difference in such a case was probably due to the fact that with the tinfoil the heat from insulation losses was not absorbed and the temperature of the insulation rose with corresponding increase of loss until failure occurred. In the case where the massive brass electrodes of small area were used on the same insulation, the mass of the brass and its radiation surface were sufficient to absorb the watt loss in the insulation and kept the temperature moderate and prevented the insulation reaching the unstable condition where the watt loss increased the temperature, and the rising temperature increased the watt loss indefinitely to failure without increase of voltage.

It is the writer's experience that instantaneous puncture voltage tests or tests of very short duration are of rather limited value in furnishing data for judging the use to which the insulation can be put, and only a test lasting long enough to give the approximate ultimate breakdown value with long continued application of the voltage will give the information desired.

C. E. Skinner: As I began insulation work rather early in the art, I think it might not be out of place to review very briefly some of the steps which have been taken in that work. The regular testing of dielectrics and the dielectric tests of apparatus began, with the company with which I am connected, early in the year 1890. At that time we had little or no information to guide us, either as to what dielectric stress meant or anything concerning the effect of the shape of terminals, and 10,000 volts was an almost unheard-of voltage to work with. During the five years that followed, the dielectric testing of materials covered practically every known material and many that probably should have been unknown, and tests of many things that proved not to be dielectrics.

During that early period I think the insulation engineer was one of the most disliked and maligned individuals in the whole engineering profession. The designer calculated to a nicety the copper and the iron, and space used for insulation he considered lost. Furthermore, the more insulation put on, the hotter the machine would get, because the insulating material was also heat insulating material. It was, therefore a constant struggle between the insulation man and those responsible for the rest of the design.

In spite of the more than twenty years of work that has been regularly done since dielectric testing came into vogue as a regular test in practically all large manufacturing establishments, the present state of the art is most chaotic.

I hope that this paper will culminate in a better set of testing specifications. We have heard in the last two days in our

committee meetings a good deal about cooperation. The American Society for Testing Materials has a committee whose duty it is supposed to be to formulate specifications for testing insulating materials. It appears to me that it is more the function of that Society to formulate a detail specification as to methods of testing than it is of this Institute, but that Society cannot do this work without the cooperation of the Institute and it is probably the function of the Institute to formulate something as to the electrical end of this work. I hope that this can be done. I know that a certain amount of work has been done in trying to arrive at a test which will give what we might call the endurance of insulation, which is really the thing that we want to know when we design our apparatus. I agree with Mr. Jackson and others that the instantaneous value is of comparatively little worth in design work. I learned very early to use a very large factor of ignorance in applying the results of my instantaneous values, because I found for example, that when thin sheets of insulating material went into a dynamo, and passed through manufacturing steps, the dynamo, as a whole, would have nothing to compare in dielectric strength with the values per mil which might be obtained on the thin sheets. There are many reasons for this lower value outside of the strength of the material itself; the workmen in the shop may contribute something to lowering the dielectric strength of the materials given them to put on the machine.

I feel that the conclusions arrived at in the paper might possibly be subject to some modification if the tests were made under different circumstances, such as a change in the testing transformer, a change in the method of applying the voltage, a change in the pressure, etc.

I think it would hardly be right in this meeting not to mention the classical work on dielectrics done by Rayner in the National Physical Laboratory. That work followed and completed, for thin materials, a mere start which was made a number of years ago by Mr. Miles Walker and myself, and published in the Institute TRANSACTIONS[3] for the year 1902. Mr. Rayner carried it to a great length, and by measuring the dielectric losses was able to predict when his insulating material was going to break down.

I feel that the future work along this line will have more to do with the study of the power factor, and the study of the dielectric losses, and the study of the endurance of the insulation under continued stress, and I hope that before another year the Institute may be able to adopt the electrical end of a scheme for the endurance test, and possibly for the loss test of insulating materials. I think this paper will do much to bring to us the importance of a standardization of methods, and in such standardization we must necessarily pay attention to every detail in order to arrive at results which would be in any way comparative when made in different laboratories and when made with different materials prepared under different conditions.

3. Vol. XIX, page 1047

H. W. Fisher: When we first commenced to use varnished cloth as an insulation for cables, it was necessary to design an apparatus by means of which we could determine the insulation resistance, the electrostatic capacity, power factor or dielectric loss and dielectric strength of different kinds of cloth. In order to accomplish this, the following apparatus was designed.

Two circular disks were made with a circular groove in each, the inside diameter of this groove being one foot (30.5 cm.). Into these grooves were fitted high-grade rubber gaskets, the ends of each of which almost came together at the top. One disk was mounted rigidly in a vertical position; the other disk was provided with insulators and on an auxiliary frame were four horizontal screws, the ends of which were inserted into insulated posts on diametrically opposite parts of the movable disk. By means of these screws the movable disk could be tightly clamped against the fixed disk so that the rubber gaskets of each would be directly opposite each other. The varnished cloth to be tested was placed between the disks, and pressure applied so as to make a tight joint between the rubber gaskets and the varnished cloth. Attached to the stand of the apparatus was an iron box containing mercury and from the box there were two rubber tubes which connected with a suitable valve at the bottom of each disk. By opening the valves and raising the mercury box, mercury was allowed to flow on each side of the varnished cloth until it reached the small aperture at the top of the rubber disks. Then the valves were closed, the mercury box was lowered to its normal position on the base of the apparatus and the rubber tube attached to the insulated disk was removed, after which the tests mentioned above were made, ending with the breakdown voltage test.

By means of this apparatus, samples of varnished cloth of different manufacture were tested and the power factors were found to vary approximately from four or five per cent to twenty per cent. By making various tests and profiting thereby, the quality of the varnished cloth was very much improved.

It was next necessary to design another type of apparatus for testing cloth in strip form, the way it occurs mostly in the trade. In order to be able to test narrow strips without flash-overs around the edges of the strips, the following plan was devised. A strip of brass about $\frac{1}{4}$ in. (6.35 mm.) wide was placed on a wooden board so that one or two thicknesses of varnished cloth could be put underneath the brass. The brass strip formed the lower electrode of the apparatus. The upper electrode consisted of a copper strip about $\frac{1}{8}$ in. (3.2 mm.) wide, mounted on insulated arms so that it could be swung to one side when not in use. The general plan is to put vaseline over the varnished cloth which is placed underneath the lower electrode so that the narrow strip of varnished cloth to be tested

can be placed centrally over the lower electrode and parallel with it and the edges of the cloth pressed firmly into the coating of vaseline, after which the upper electrode is turned over so as to drop in position above the lower electrode. In this way, puncture tests of varnished cloth can be made without any danger of flash-overs around the edges of the strip of cloth tested.

In the testing of cloth with electrodes of different lengths or diameters, care must be taken to proportion the number of tests made to the areas tested. In other words, if a test is made to determine the relation between tests with disks 1 in. (25.4 mm.) in diameter and with disks 20 in. (508 mm.) in diameter, 400 tests should be made with the 1-in. diameter disk, to one test of the 20-in. disk, and the minimum of the 400 tests taken as the tests which ought to correspond to the one test on the 20-in. disk. Bearing this in mind, we made a number of tests which do not show at all the difference indicated by Mr. Farmer's figures. I think that he did not make enough tests of the larger electrodes to get a fair comparison. In order to make a check with a view to determining if the above theory was not correct, we took a roll of cloth and made forty tests consisting of five groups of eight, with electrodes 1 in. (25.4 mm.) long, and then got the average of the minima of these. Next we took the average of ten tests made with electrodes 8 in. (203 mm.) long, and the two sets of measurements agreed within two per cent.

For the same reason just explained, a short length of cable will almost always withstand a higher voltage test than a long length of the same cable.

The old Underwriters' rule was to apply a test of 3000 volts per 1/64 in. (0.397 mm.) of insulation on a one-foot (30.5-cm.) sample. Wire insulated with almost any kind of rubber would withstand that test on a one-foot sample, whereas a coil of wire would break down under the test of 3000 volts per 1/64 in.

M. E. Tressler: Last January when making some very similar tests on yellow varnished cloth I obtained practically the same shaped curves as Mr. Farmer has with various sizes of electrodes from 1 mm. to 100 mm. in diameter with approximately square edges.

A curve showing this variation in disruptive voltage with diameter of electrode for 10 layers of yellow varnished cloth tested under oil at approximately 25 deg. cent. was published last winter[4]. At the same time tests were made on various numbers of layers from 1 to 20 and with electrodes whose edges were rounded to different radii from 0 to 10 mm.

My results do not show such a decided difference between the disruptive voltages with small and large electrodes as do Mr. Farmer's. The maximum disruptive voltage was 1100 volts per mil with a 5-mm. electrode and 810 volts per mil with the 100-mm. electrode.

4. *General Electric Review*. March, 1913—Tressler.

This total decrease is about 26 per cent, of which about 20 per cent took place between the 5-mm. and the 20-mm. electrodes, indicating that tests on thin insulating materials could be made with any convenient size of electrodes from 25 to 100 mm. in diameter and practically the same results would be obtained with a given material.

With greater thicknesses of insulation up to 240 mils, the variation of disruptive voltage with the size of terminal decreases, until at 240 mils there is no difference between the disruptive voltage with 5-mm. and 100-mm. electrodes. However, all of these tests were made by increasing the voltage steadily until breakdown occurred, *i.e.*, the voltage was on from 6 to 12 seconds for Mr. Farmer's tests and from 4 to 8 seconds for mine. This is not a sufficient length of time to allow the

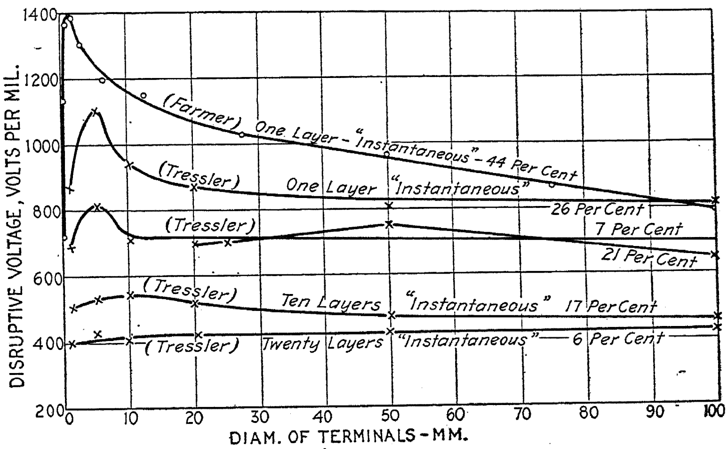

FIG. 3

insulation to be affected by the heat from the energy loss due to the alternating potential.

It would be a much better indication of the disruptive voltage of an insulation under working conditions, if "one-minute" tests were made, *i.e.*, use 50 per cent of the "instantaneous" disruptive voltage as a start for the "one-minute" test and increase by 10 per cent steps each minute thereafter until breakdown occurs.

In general the "one-minute" test will give lower disruptive voltage than the instantaneous test. Sometimes the disruptive voltage increases with increase of temperature and hence we would expect that the "one-minute" test would be equal to or higher than the "instantaneous" test.

If we use the "one-minute" test in finding the effect of terminals of different sizes we will see there is much less dif-

ference between the disruptive voltage with 1-mm. terminals and 100-mm. terminals for any thickness of insulation.

I agree with Mr. Farmer that we are very much in need of standard specifications for the testing of insulating materials, and would recommend, briefly, the following:

1. "One-hour" tests where possible, the "one-minute" puncture voltage being used to indicate the starting voltage for the "hour" test.

2. For testing solid insulations: flat disk electrodes 10 cm. in diameter with practically square edges and insulated on the sides to prevent corona and arcing.

For testing liquid insulations: flat disk electrodes 25 mm. in diameter with practically square edges and spaced with faces parallel and 2.5 mm. apart.

3. All tests of solid insulation should be made under oil when possible and with a pressure of 100 g. per sq. cm. applied by the terminal to the insulation.

4. Two temperatures of test should be considered standard; one at 25 deg. cent. and the other at the highest "hot spot" temperature allowed on the given insulation to be tested.

5. The insulation for test should be 2.5 mm. thick or as near thereto as possible.

With these tests complete on a given insulation we would be able to judge very closely whether the insulation in question was suitable for the place and work required of it.

A better indication of the value of an insulation for high or moderate voltages would be to measure the thermal conductivity at different temperatures and the energy loss at various voltages and temperatures.

Then if the insulation had a large energy loss and low thermal conductivity we would know that it would not be of much use as a high-voltage insulation, whereas if the energy loss were small and the thermal conductivity high we could be sure of a very good insulation, so far as electrical properties are concerned.

Of course we must consider the kind of insulation being used, whether organic or inorganic, how treated and at what maximum temperature it could be run continuously.

In reply to one point brought up by Mr. Thomas, the distortion of the voltage wave across the insulation, I would say that several years ago when testing a piece of insulation of comparatively high permittivity between 25-cm. disk terminals at 50,000 volts, Mr. A. B. Hendricks took an oscillogram of the current wave in the insulation and found it to be practically a sine wave. If there had been any appreciable harmonics in the high-potential voltage wave they would have been magnified by the capacity, in the current wave; hence we may readily assume that, since the current was a sine wave, the voltage also was a sine wave.

E. B. Rosa: I would like to emphasize what has been emphasized already by several of the speakers, and that is the

advantage of having something like standard methods for making insulation tests, and also the advantage of making energy measurements in addition to the breakdown measurements. The measurement of the power factor of the current flowing through such a dielectric reveals wonderful differences, much greater than one would expect. A plate of mica will have a very small power factor, its angle corresponding to the power factor being as small as one minute of arc. That is, the angle by which the current differs from a 90-deg. advance of the e.m.f. is as small as a minute of arc, or smaller. As Mr. Fisher says, in some materials it may be 20 deg., may range anywhere from a minute, or less, to many degrees, so that the heating effect and the energy expended may vary through a range of a thousand to one, and, naturally, if the heating effect is large, the dielectric strength will sooner or later be very much affected.

The work of Dr. C. Kingbrunner, at the Technological School at Manchester, about eight years ago, was very carefully done, and is quite an extended piece of investigation. He stated that he found the values of the dielectric strength to vary with the pressure, and as the pressure was decreased gradually, it finally became constant. He gives a curve showing the relation between the pressure and the measured dielectric strength, using a pressure of 500 g. per sq. cm., beyond which the value was constant. He also stated that electrodes of greater diameters than two cm. vary appreciably. He used a diameter of four cm. in order to be sure to have them large enough. These results are different from those cited in the paper, and illustrate the need of taking account of previous work and also of having all the work that has been apparently carefully done, and has been published, reviewed by some co-ordinating agency in order that the best results may be reduced for all this work.

I was very much interested in what Mr. Skinner said about coöperation in solving such a difficult problem, or, at least, making progress with such an important and difficult problem as this, and as he is so thoroughly convinced of the need of it, it is encouraging, because he is in a fortunate position to bring about such coöperation, as chairman of the committee of the American Society for Testing Materials.

Clayton H. Sharp: The facts in Mr. Farmer's paper, and these other data that have been presented tonight, show more than anything else the elusive character of the problem of testing insulation. It is a case of " now you get it " and " now you don't get it ", and just why these curious effects occur is, of course, a matter of very great importance. I do not think that the phenomena which occur are quite so easily explained as one of the speakers tonight would have us believe. Mr. Farmer's results alone show that the matter is more complicated. The question of averages undoubtedly enters, but there is something more than that to it.

Here we have one of the most important elements which enters into the construction of all electrical machinery and apparatus, and it is quite evident that we are unfamiliar with a good many of the fundamental and underlying attributes of this material. It is, therefore, very necessary that further researches of the character of these which Mr. Farmer has made, and of more extensive scope, should be carried on. In the meantime, for the purpose of the practical testing of apparatus, it is of very great importance that some standard specification should be prepared and should be followed.

John B. Taylor: We have here a paper dealing with stresses in insulating mediums, without formulas or mathematical symbols, and yet perhaps of more practical application than some of the papers in the last few years on corona and the distribution of stresses around points, spheres, and other shapes. The curves and results discussed in the paper are quite different from those the theories would seem to lead to. As the paper offers no explanation of these results, it is to be regretted that it is not more complete in a few respects so that the conclusions can be either accepted or doubted for good reason.

There seem to be three factors which may account for the lower breakdown strength per mil as the size of the surface covered is increased. In the first place, if the testing transformer is small, the increase in capacity would tend to raise the voltage on the test specimen without raising it by the same amount on the low-tension voltmeter. Second, as previously brought out, when dealing with a larger sample, by the law of chances we ought to find some weak spots. Third, with the larger sample there is less chance for the radiation of heat. Since all three of these factors work in the same direction, a combination of them may account for the results given.

Mr. Tressler has given some information which corroborates, although not to the same degree, the general character of the results. My own first impression was that the heating was the most likely factor, but this impression does not hold after seeing that the voltage has been brought up at the rate of 1000 or 1200 volts per second, and as the specimens are only 10 or 12 mils thick, the whole test is over in eight or ten seconds. That leads me to ask how it is possible to establish the figures of volts per mil to some four or five parts in a thousand, when the voltage is changing so rapidly.

Also, I would like to ask if the failures in general occur at the edge of the different disks, or whether they are just as likely to occur in the middle.

It would seem desirable to give, in tabulations like these, the average deviation of the results from the mean result. The maximum and mean are given, but the average deviation gives a better idea of the concordance of the observations.

I have a suggestion to make. Many tests of this sort might be made with direct current, which would eliminate some of the

uncertain factors when dealing with alternating current. The heating factor would be eliminated, and also the question of voltage ratio and capacity factor.

A. E. Kennelly: The subject matter of the paper appears upon its face to be very simple. We have here flat electrodes, and except when the electrodes are very small—half a centimeter or less in diameter, we can hardly avoid the conclusion that the stress which ought to be imposed in a uniform dielectric between such flat electrodes is substantially uniform over the entire surface, and we also all believe, I think, that uniform homogeneous material breaks down electrically at the same electrostatic flux density, which means when the maximum local gradient of potential attains one and the same breakdown value.

Starting from this premise, where we would naturally suppose that for the same thickness of material, like varnished cambric the breakdown stress should be the same for different sizes of the different diameter of electrodes, from 0.5 cm. to 10 cm., or more, the values given in the paper show that they are not the same. How are we to reconcile these inconsistencies?

If we assume that there is air pocketed in thin films somewhere, then we have the three dielectrics, air film, varnish film, and the cambric, and these three layers are capable of being associated in various thicknesses which might give rise to variations of electric flux-density and gradient.

It has been pointed out by several of the speakers that one of the conditions involved is the relative chance of including weak spots; but, as has been pointed out by the author of the paper, if that were the case, we should certainly expect what may be called the probable error to be much greater for the little electrodes than for the big electrodes, and if the probable error were greater, the difference between the maximum and minimum voltages of the ten samples would certainly differ very materially, whereas actually, an inspection of the tests indicates that substantially there is the same difference between maximum and minimum voltages in the ten tests on each particular size of electrode. We cannot find an explanation here in the different probabilities of including weak spots.

Since this remarkable variation of dielectric strength with electrode diameter does not seem to be explained satisfactorily, it becomes the more important to standardize the dimensions of test electrodes until the matter has been cleared up.

H. M. Hobart: The subject which is uppermost in my mind at the present time is the need of establishing some relation between the rate of aging of insulating material and the temperature to which it is subjected. From experience with apparatus in service, we have a good idea of this relation up to a little over 100 deg. cent., but we want to consider how far we can go in the direction of higher temperatures with conservatism. As for the range between 110 deg. cent. and 200 deg. cent., the data at our disposal are very meager indeed. The meagerness of our

data relating to aging is rather discouraging. One cannot afford to wait several years for the results of aging tests before employing attractive methods of insulating machines. Nevertheless, the sooner we embark upon elaborate aging tests the sooner we shall have the results commercially available. If a certain material ages imperceptibly at 100 deg. cent., it may age with decided rapidity at 200 deg. cent. If we were to maintain a number of samples at a temperature of 200 deg. cent. the results obtained in a week or a month might be very instructive. We could bake one set of samples at 180 deg., another at 160 deg., another at 140 deg., and another at 120 deg., and take out samples periodically from the ovens. From the results we should be able to establish a curve for that particular insulating material which would give a clue to what we could do with that material in insulating commercial machines. When used in the construction of slot insulation, it might not conform closely to the results which would be obtained by samples tested in the laboratory, but the results would, nevertheless, be indicative.

There is a matter of considerable importance to which I should like to allude. In a paper recently read before the Institution of Electrical Engineers of Great Britain by Mr. S. Evershed, a very interesting footnote appears in which the author states: "The flash test as applied to some costly piece of electrical apparatus must have been inspired originally by something akin to the heroism of the savage." Ever since the time to which Mr. Skinner alludes we have been making tests on electrical machinery not very unlike flash tests. Such tests are still made and are jeopardizing the subsequent life of the machines. The machine may survive the test, so far as we can perceive, but we do not know that we have not caused some serious damage to the machine which will make it of less service during its working life.

W. I. Middleton: In the breakdown tests of cambric cloth insulation, I have used 12 in. (30.48 cm.) electrodes rather than smaller ones, believing the results would be nearer the average breakdown value of the cloth.

My experience with the large and small electrodes has been very similar to that of Mr. Farmer. Between the large and small electrodes, 12 in. (30.48 cm.) and 1 in. (2.54 cm.), I have found an average difference of about 50 per cent increase with the smaller ones. Other investigators have found similar results when investigating along other lines. Mr. Fisher says the short length of cable will stand more voltage than the long length, and my own experiences with the short samples of cables have proved this to be so. Experiments with corona on bare wires have shown that the corona starts at a lower voltage on long lengths than on shorter ones. There is evidently some fundamental law underlying all of these results, although the experiments have been along lines so very different.

In regard to the probability law, we have experimented with

different insulating materials, trying to find one that would give consistent results, and have found none that was as good as air, the oil breakdowns being very irregular. The breakdown of air about the wire, as regards long and short lengths, is so similar to that of other insulations that it would appear to eliminate the law of probability, as we can hardly say that there are weak places in the air.

The chances of wave distortion with any samples of cambric, even as large as 1 sq. ft. (0.0929 sq. m.), seem to be very slight, as the charging current would be very small; this is quite possible where the charging current is considerable, as with long lengths of cables.

The instantaneous breakdown has many advantages in this class of work, if properly applied, as it allows a great many samples to be handled in a short time and eliminates the heating effect, which is one of the most difficult elements to analyze in work of this kind.

I believe we should have a standard size of electrode for this class of work so that the results of tests made by different investigators may be more readily compared, having this large element of doubt as to size of electrode removed.

F. M. Farmer: As to the matter of weak spots—the weak point theory seems to stick with a good many, even though Dr. Kennelly has pretty well covered it. This was pretty thoroughly discussed in the paper. Suffice it to say that it is not at all to be expected that the curves, each point on which is made up of ten tests, would all be smooth and all follow the same general shape. Furthermore, the shape is similar to that obtained for oil where there is no question of weak spots.

The possible effect of distortion with the large electrodes has been mentioned. We went into the matter pretty carefully, and could find absolutely no distortion of the wave with specimens up to 15 in. (38 cm.) in diameter and potentials up to 15,000 or 16,000 volts. A 10-kv-a. transformer was used.

As to the matter of heating, I do not think there can be very much in that as an explanation of these results, because the tests were of such short duration—only a few seconds. From a commercial standpoint the heating should undoubtedly be taken into account. If we want to get at the dielectric strength of the material under operating conditions undoubtedly the temperature has got to be taken into consideration, as also have pressure, and various other things. The point of this paper was simply to call attention to one of the variables and how much it does vary. Each of us is in the habit of making these tests along certain lines, and each has established his own standard electrodes, but it is well to know at least in a general way what the effect of using other electrodes might have been. It was also hoped to show the desirability of standardizing one size, for one size is as good as another because the results are quite empirical,—each designer must apply his own factor of safety.

We have standardized specimens for testing steel, but the designer does not think of using the steel in his structure up to the values given in the test. He allows a factor of safety according to the conditions.

Specifications for insulating cloth should be prepared with a view to enabling us not only to make the tests quickly and cheaply on small samples, but so that everybody will understand what they mean. Then let each individual apply his own factor of safety to suit his own conditions.

Mr. Taylor evidently wanted some more theoretical explanations. There is ample opportunity for those so inclined to make theoretical speculations. I have been unable to formulate a satisfactory explanation and that is why none is offered in the paper. Mr. Peek seems to think the matter very simple, but I do not think so. I do not see how the theory which he advances with respect to cylindrical and spherical electrodes can be applied to flat disks, where the distribution of the flux is very different.

Mr. Taylor apparently has concluded that the potential was measured to five volts and very properly questions such refinement. These figures in the paper are not single measurements, however, but in each case the average of 10 measurements rounded off to the nearest five.

Mr. Taylor asks if punctures appeared near the edges of the electrodes more frequently than elsewhere. The punctures were pretty fairly distributed over the entire surface, which I think is accounted for by the rounded corners.

J. W. Milnor (communicated after adjournment): There has been considerable speculation concerning the causes of the phenomena observed by Mr. Farmer, and in view of this an analysis based on the theory of probability should be of interest.

Let it at first be assumed that the electric field between the electrodes is uniform, the increased flux density near the edges being ignored. The total area of the insulating material under test may be considered to be made up of a large number of elemental areas dA having an average dielectric strength E_a, this value being very high. Their dielectric strength should vary according to the well-known law of error. That is, the probability curve of dielectric strength of an element of area is

$$P = \frac{h}{\sqrt{\pi}} \epsilon^{-h^2 (E_a - E)^2} \tag{1}$$

in which h is a constant. If the area of one of the testing electrodes is A, we have $\frac{A}{dA}$ elements of area included between the electrodes, and the whole dielectric will fail at the weakest element of area. To estimate this dielectric strength, let

the area under the curve given by equation (**1**) be divided into $\frac{A}{dA}$ equal parts. Then the dielectric will most probably fail at the voltage represented by the center of the lowest section. This is near the boundary of the lowest section if the area is divided into $\frac{2A}{dA}$ equal parts.

The area under the probability curve included between the ordinate $(E_a - E)$ and the ordinate at negative infinity is given by the series

$$\text{area} = \frac{\epsilon^{-h^2(E_a - E)^2}}{2\sqrt{\pi}\, h\,(E_a - E)}\left[1 - \frac{1}{2\,h^2\,(E_a - E)^2} + \frac{1.3}{4\,h^4\,(E_a - E)^4} - \ldots\right], \quad (2)$$

and since the total area under the curve is unity, each member of equation (**2**) is equal to $\frac{dA}{2A}$. Therefore

$$A = \frac{\sqrt{\pi}\, h\,(E_a - E)\cdot dA\cdot \epsilon^{h^2 E_a^2}\,\epsilon^{-2\,h^2 E_a E}\,\epsilon^{h^2 E^2}}{1 - \dfrac{1}{2\,h^2\,(E_a - E)^2} + \dfrac{3}{4\,h^4\,(E_a - E)^2} - \ldots}, \quad (3)$$

Now if dA is decreased indefinitely, E_a becomes very large, so that E is small in comparison, and h becomes very small. In the limiting case, with dA infinitely small, equation (**3**) becomes much simplified, and the result is of the form

$$A = C_3\,\epsilon^{-C_4 E} \quad (4)$$

Solving for E,

$$E = \frac{1}{C_4}\log_\epsilon C_3 - \frac{1}{C_4}\log_\epsilon A = C_1 - C_2\log_{10} A, \quad (5)$$

in which C_1, C_2, C_3, and C_4 are constants.

Equation (**5**) shows that the dielectric strength of thin insulating material should vary as a simple logarithmic function of the area of the testing electrodes when conditions are such that the effects of the edges of the electrodes are small. It is evident from equation (**5**) that if n separate tests of a given dielectric are made, using the same set of electrodes the difference between the average result and minimum result of the n tests

is most probably equal to $C_2 \log_{10} n$, this value being independent of the area of the electrode. It may also be shown that when n is large the average deviation of the individual results from their mean is approximately 0.43 C_2, no matter what the area of the testing electrodes.

The increased electric flux density which occurs near the edges of the electrodes causes the observed dielectric strength to be generally less than called for by equation (**5**), and this discrepancy is larger, the smaller the area of the electrodes, or the greater the thickness of the material under test. This is evident when it is considered that either decreasing the area of the electrodes or increasing the thickness of the dielectric increases the

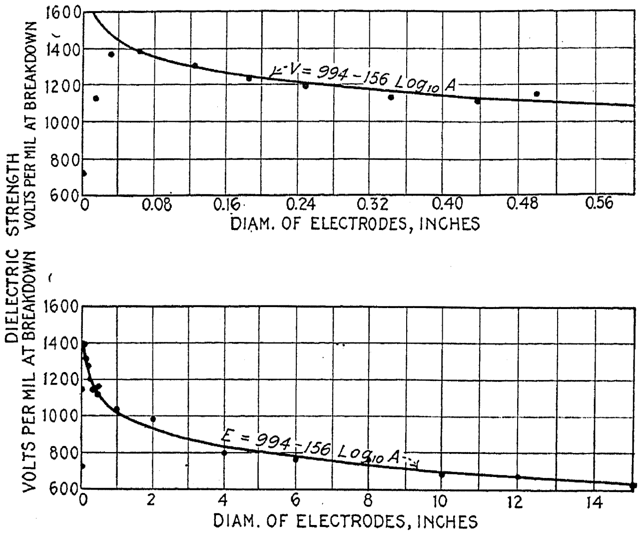

FIG. 4—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WHEN TESTED IN AIR, SHOWING AGREEMENT WITH THEORETICAL CURVE.

ratio of the maximum stress to the average stress, and also increases the proportion of the total area that is subjected to this maximum stress. When testing a single thickness of varnished cambric, relatively few of the failures occur near the edges of the electrodes; but when testing five or ten layers simultaneously, it will usually be found that a large proportion of the failures occur near the edges.

In order to illustrate the application of equation (**5**), the data given by Mr. Farmer for the dielectric strength of varnished cambric have been replotted (Fig. 4 herewith), and in the same figure has been drawn the curve

$$E = 994 - 156 \log_{10} A, \qquad \textbf{(6)}$$

the area being in square inches. The constants of this equation were determined by trial. The curve agrees very closely with the observed data when the diameter of the electrodes is 1/16 in. (1.588 mm.), or greater. When the diameter is less than 1/16 in. the effect of the edges predominates. The difference between the average and the minimum results of the tests with a given electrode should be 156 $\log_{10} n$, being the number of tests. When n is 10 this difference is 156 volts per mil at puncture; if n is 15 the difference is 183; if n is 21 the difference should be 206, etc. It will be observed that these differences as obtained from Table I of Mr. Farmer's paper are not greatly unlike the values given above.

The foregoing discussion indicates that the peculiar variation of the dielectric strength with the area of the testing electrodes is due mainly to irregularities of the material under test when the area of the electrodes is large, and to increased maximum flux density when the area is small. In deciding upon a size of electrodes to be adopted as standard, the area should be large if the aim of the tests is to determine the most representative value of the dielectric strength with the fewest number of tests. If, however, the most reliable result is desired while a minimum quantity of the material is used, a set of electrodes of small diameter should be chosen.

Presented at the meeting of the Schenectady Section of the American Institute of Electrical Engineers, Schenectady, N. Y., December 16, 1913.

POWER FROM MERCURY VAPOR

BY W. L. R. EMMET

The theoretical limit of efficiency in a thermo-dynamic process is the ratio of the temperature range embraced by the process to the maximum absolute temperature used, $\frac{T - T_1}{T}$ In all processes available for commercial power development, the lower limit is fixed by the temperature of cooling water available, and is therefore not susceptible of variation. The possible upper limit is the temperature which can be produced by our fuel when burned with air, which in practise is about 2700 deg. fahr.

The purpose of the process here described is to utilize some of the energy available in ranges above that which can conveniently be utilized with steam. The theoretical efficiency of steam processes can be increased by using higher pressures, but since with rise of temperature the increase of pressure is very rapid, and since the steam turbine has limitations in the efficient use of high pressure, prospects of gain in this direction are not very attractive.

Mercury boils at 677 deg. fahr. at atmospheric pressure and condenses in a 28-in. (711-mm.) vacuum at 455 deg. fahr. It is therefore well adapted, at least by pressure and temperature conditions, for use in a temperature cycle above that now used with steam. Its use to increase greatly the temperature range available, and so to increase efficiency, is the object of the development here described.

Before going further, the writer desires to explain that the principle involved in this process was suggested to him by Mr.

Charles S. Bradley, who proposed and patented a quite similar process in which he intended to use certain other substances of high boiling point and relatively high vapor density. It has since been learned that there have been other proposals along similar lines, although none of them have involved the use of mercury. Consideration of the possibilities suggested by Mr. Bradley led the writer to study the characteristics of mercury, and from this study and a course of experimenting which has been going on for a year, the plans of procedure here shown and explained have been evolved. A set of apparatus suited to the production of about 100 h.p. has been nearly completed and it is hoped that experiments on a scale and of a character approaching commercial conditions may be made within a month or two. Anything so completely novel and so essentially complicated is naturally liable to delays, so that the prospect of successful tests cannot be confidently predicted. Since the process has been talked about and since a good deal of interest has been expressed, the writer has thought best to record his expectations and to make explanation of the plans which have so far been evolved.

In studying the thermodynamic possibilities of a substance like mercury, we proceed exactly as we do in the case of steam, and for the sake of convenience it may be well to give here some data relating to the subject.

Boiling point of mercury at atmospheric pressure	677 deg. fahr.	(358 deg. cent.)
Boiling point of mercury at 28-in. vacuum	457 deg. fahr.	(236 deg. cent.)

Vapor density is in the ratio of atomic weight and absolute temperature; as compared with water the vapor density of mercury is therefore 6.56 times as great at the boiling point and 6.8 times as great at 28-in. (711-mm.) vacuum.

Specific heat of mercury liquid	0.0373
" " " gas, (constant pressure)	0.0248

(According to Kurbatoff; *Zeit. Phys. Chem.* 43, 104, 1903).

Latent heat of vaporization—

at 25 lb. (11.3 kg.) abs.	$r = 117$	B.t.u.
" 15 " (6.8 kg.) "	$r = 118$	"
" 28-in. (711-mm.) vacuum	$r = 121$	"
" 29-in. (737 mm.) "	$r = 121.5$	"

(Calculated from formulas by Kurbatoff).

The boiling point of mercury at various pressures is shown by an accompanying curve, Fig. 1, and curves are also given in Fig. 2 showing the energy theoretically available from mercury vapor within various pressure ranges. These curves are calculated from Rankine's formula:

$$E = 778 \left[Q_1 - Q_2 \left(1 + \log. \frac{Q_1}{Q_2} \right) + \frac{x_1 r_1}{Q_1} \ (Q_1 - Q_2) \right]$$

E = energy in ft-lb.
Q_1 and Q_2 = heat of liquid.
x = dryness factor.
r = latent heat.

The data above stated may not have been as accurately determined as those which are available for steam calculations, but their substantial accuracy is indicated by the fact that in our experiments, the measured flow of vapor through nozzles has closely checked the calculations.

The method applied in this process may be stated briefly as follows: Mercury is vaporized in a boiler heated by a furnace of ordinary type. From this boiler (see Fig. 3) it passes at a pressure near or not much above the atmosphere, to the nozzles of a turbine which drives a generator or other utilizer of power. From this turbine it passes to a condensing boiler where it is condensed on the outer surface of tubes which contain water, and this water is vaporized by the heat delivered, and the steam produced is used to drive other turbines or for any other purpose. This condensing boiler is preferably placed at a level above the mercury boiler, so that the condensed liquid will run back into the mercury boiler by gravity without the aid of a pump. Since the mercury vapor is much hotter than the steam, the gases will normally leave the mercury boiler at higher temperatures than they have in leaving a steam boiler. To utilize this excess heat in the gases, it is proposed to convey them first, after leaving the mercury boiler, through a heater which raises the returning liquid almost to the boiling point, second, through a superheater which superheats the steam delivered by the condensing boiler, and third, through an economizer which heats the feed water for the condensing boiler and so reduces the gases to the lowest practicable flue temperature.

By careful study and experimental development, which will be later explained, means have been devised for reducing the amount of mercury used, for effectively preventing its loss or

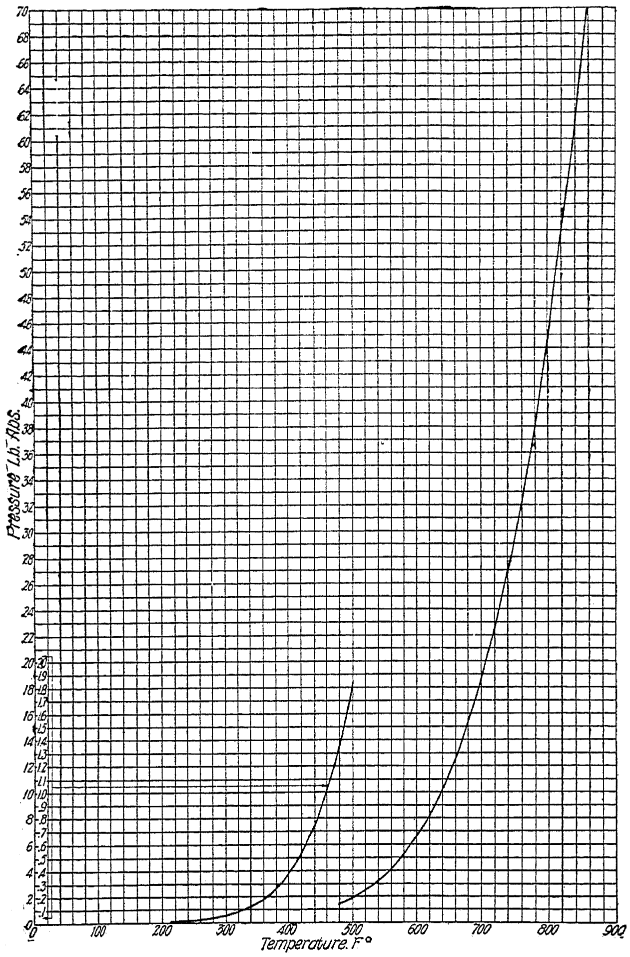

FIG. 1—CURVE SHOWING BOILING POINT OF MERCURY AT VARIOUS PRESSURES

dissipation, and for immediately detecting any failure in such prevention.

The disadvantages of mercury for such a process are: First, that it is very expensive, its cost being about 60 cents per lb.

($1.32 per kg.). Second, that it is poisonous and is capable of pervading the atmosphere in a very finely divided state in the neighborhood of places where the vapor can escape. Third, there are certain difficulties in confining both the vapor and the liquid, although these, with proper methods, are not serious.

Mercury's advantages as a thermodynamic fluid for the

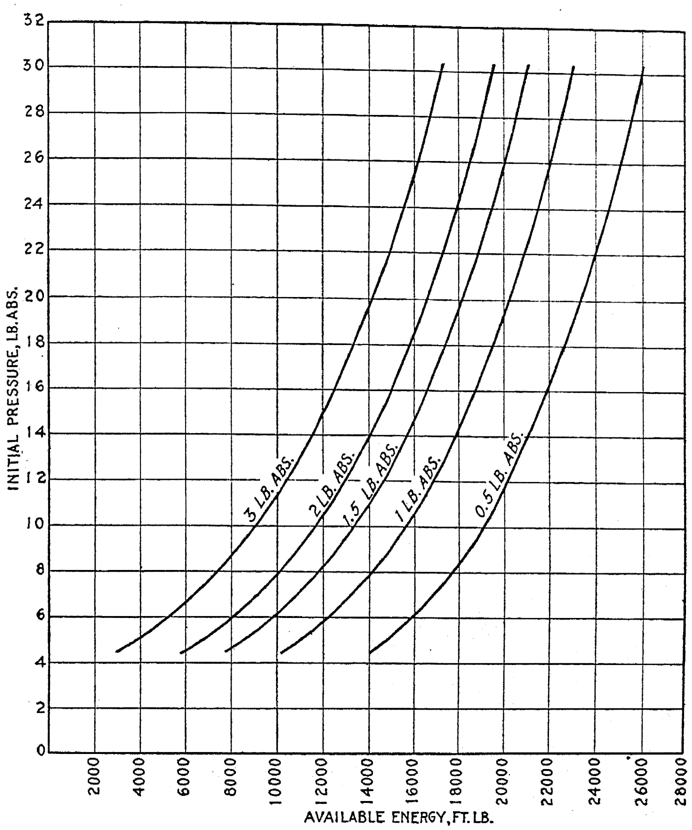

FIG. 2—ENERGY THEORETICALLY AVAILABLE FROM MERCURY VAPOR WITHIN VARIOUS PRESSURE RANGES

purpose desired are many. First: its boiling points at desired pressures are convenient. Second: its high specific gravity makes possible the use of gravity feed, sealing of valve stems, etc., and centrifugal sealing of turbine packings. Third: it is completely neutral, at the temperatures used, to air, water,

iron, and such organic substances as it may come in conta with. Fourth: it carries nothing in solution which can adhe to or affect heating surfaces, consequently the interior of boi is always perfectly clean. Fifth: its vapor density is so hi that it gives a very low spouting velocity, and consequen a very simple type of turbine can be used. Sixth: it does n wet the surface of turbine blades and consequently gives a

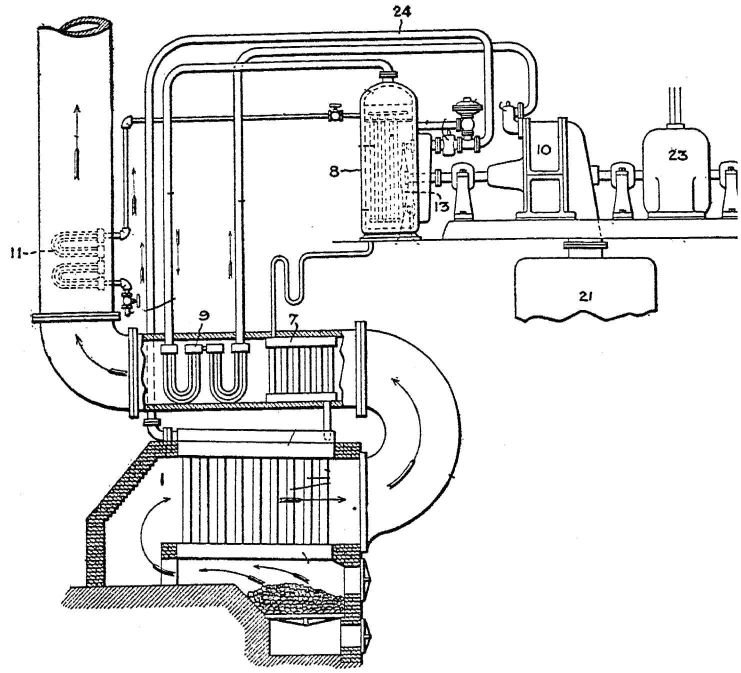

FIG. 3—DIAGRAMMATIC VIEW OF APPARATUS TO GENERATE PO

1. Mercury vapor boiler.
7. Heater for liquid mercury.
8. Condenser boiler.
9. Superheater (steam).
10. Steam turbine.
11. Feed water economizer.
13. Mercury turbine.
21. Steam turbine condenser.
23. Electric generator.
24. Mercury vapor pipe.

parently no erosion. It is believed that the action betw the vapor with its accompanying liquid and the blade sur will conduce to a high economy in a turbine, although no p tive data on this subject have yet been obtained. Sever Its volume at convenient condensing temperatures is such t it can be used in turbines without excessive bucket heig One of the greatest limits of design in steam turbines is the la

area required for the efficient discharge of the low-pressure steam. With mercury vapor, this difficulty does not exist. Eighth: delivering its heat at the temperature and in the manner which it does, the condensing boiler in which this heat is used to make steam is very small and simple as compared with a steam boiler. Steam boilers transmit an average of about 6 watts per sq. in. (6.45 sq. cm.) with an average temperature difference of about 1100 deg. fahr. A surface condenser transmits 18 watts per sq. in. with 20 deg. fahr. temperature difference. The mercury boiler is about equivalent in dimensions to a surface condenser, and since there is no high temperature involved, there will be no possibility of scaling or burning. Thus in this process we have low pressure and a clean boiler interior at the hot end, and small and perfectly distributed temperature differences at the low-temperature end of the process, where steam is made. High temperature, unequal distribution of heat, and the necessity for large heating surface constitute the principal difficulties of boiler construction. All of these are overcome in this method of making steam.

In this process the mercury vapor acts automatically as a conveyer of heat from the fire to the condensing steam boiler. If, through loss of load or other reasons, the mercury turbine admission is shut off, the vapor bypasses through a safety valve provided for the purpose, so that all the heat delivered to the mercury is immediately put into the steam boiler, except the fraction which is converted into power by the turbine.

Thus the fireman, in this process, will maintain steam pressure just as he now does. The steam produced will be used just as it now is in existing apparatus, and the output of the mercury turbines will be simply a by-product which is additional to the power which is now obtained. Studies have indicated that if this process works out as expected, the apparatus described can, in many cases, be put into the building space now occupied by steam boilers, so that the act of changing existing steam plants to this process should retain in use most of the existing investment.

Before entering into the details of experiments or of the methods by which it is hoped to accomplish these results, it may be well to state the degrees of economy which should be accomplished if this development succeeds. Assuming heat deliveries to surfaces exposed equal to those in steam boilers under

equivalent conditions of temperature difference, gas velocity, and radiation, and assuming a turbine efficiency equal to that of steam under equivalent velocity conditions, the calculation shows that in an efficient modern power station, the same amount of steam can be delivered to the turbines at the same superheat, thus giving the same turbine output, and that in addition about 66 per cent of the power so delivered can be delivered by mercury turbines, the fuel required being only about 15 per cent greater than that which would be used with the steam alone. Thus the gain in capacity of an existing station would be approximately 66 per cent and the gain of output per pound of fuel would be about 44 per cent. This calculation is based upon a mercury vapor pressure 10 lb. (4.5 kg.) above the atmosphere and a vacuum of 28.5 in. (724 mm.) at the steam turbine outlet.

About 10 lb. (4.5 kg.) of mercury would be evaporated for each pound of steam produced, the steam pressure being about 175 lb. (80 kg.) gage, superheat 150 deg. fahr., and the final temperature after gas leaves economizer being about 300 deg. fahr. The vacuum in both steam and mercury turbines can be maintained by the same air pump, means being employed to separate all mercury vapor from the air in a suitable cooler.

A non-condensing steam plant produces more than half as much power from a pound of fuel as a good condensing station, and since the mercury process can be superimposed upon a non-condensing steam process as well as upon a condensing steam process, it is obvious that with the mercury combination the non-condensing plant can be made almost as economical as the best existing condensing plants. It is also obvious that when the mercury process is added in cases where steam is less economically used than in modern power stations, the gain will be relatively greater. The purpose of the process is to replace steam boilers wherever they are used and to obtain power from mercury turbines as a by-product.

Experimental data indicate that not more than $10 worth of liquid mercury per kilowatt output of mercury turbine will be required for such a process, and it is probable that with suitable arrangements, this amount can be considerably reduced. The general application of such a process would require immense quantities of mercury, but inquiry has indicated that the sources of supply are such that the largest conceivable de-

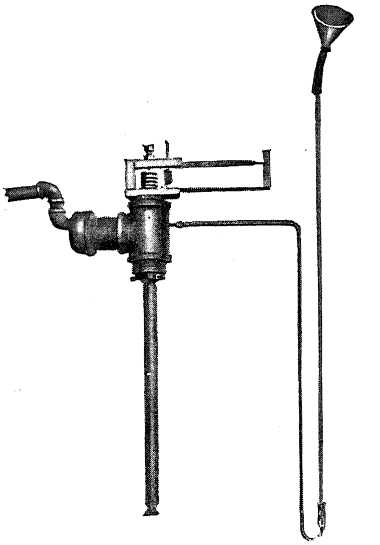

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FIG. 4
FIRST EXPERIMENTAL MERCURY
BOILER TUBE

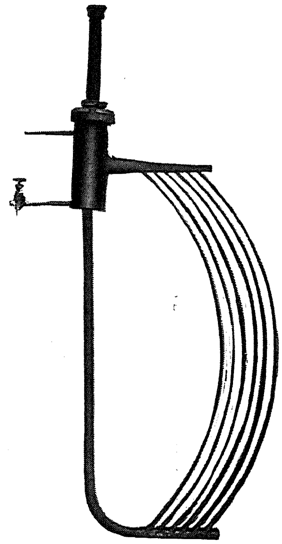

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FIG. 6
SECOND EXPERIMENTAL
MERCURY BOILER TUBE

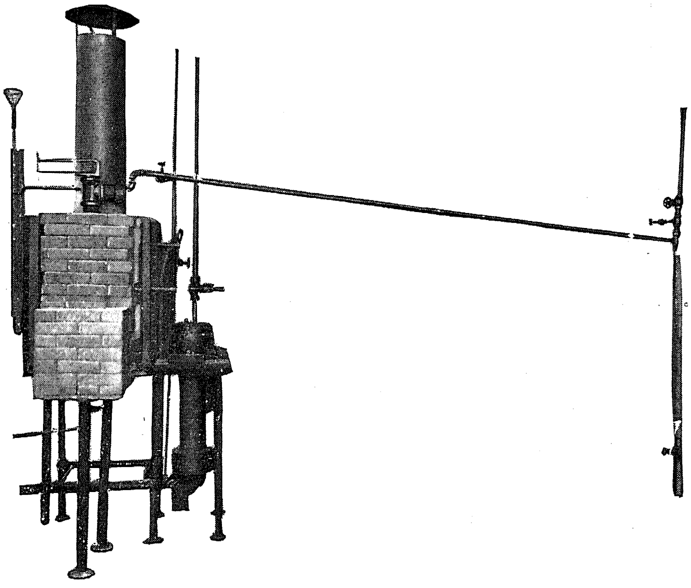

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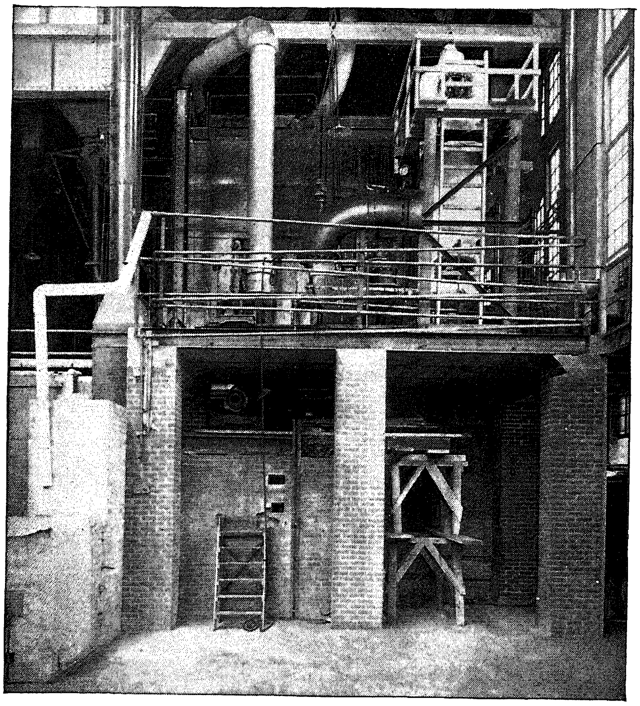
FIG. 5—MERCURY BOILER TUBE OF FIG 4, ENCASED IN BRICK SETTING



[EMMET]
FIG. 11—MERCURY BOILER AND TURBINE AS ERECTED IN POWER HOUSE

mand for such a purpose would not permanently increase the price.

In the experimental calculations of this process which have so far been made, the vapor has been produced in heating elements similiar to those proposed for an actual boiler under the most severe condition of heat delivery by gas flow and radiation. The vapor has been carried from such boiler elements to a nozzle and this nozzle has been exhausted into a condenser from which the liquid is drained back into the boiler by gravity, the vacuum being maintained in the condenser by an air pump. In this experiment the only element lacking is the turbine wheel, which, although it constitutes the only visible evidence of results in such a process, is in reality unimportant, since the nozzle is the real engine which transforms heat into motion, the movement of the wheel by the moving fluid being a mechanical matter governed by laws which are very well understood.

In these experiments, pressures and amounts of liquid condensed were measured, and these measurements show that the flow of vapor through the nozzle was in agreement with the calculations from the data above stated.

In all the tests which have been made with these experimental elements, there has not been a trace of chemical action upon the mercury or steel, although air, water, oil, and various kinds of dirt have been present in considerable quantities, and although very extreme temperatures have at times been used.

Investigation of the conditions of heat transference and circulation in the production of mercury vapor has involved much labor in study and experimenting, and through this work certain data have been collected which, in combination with known data concerning action in different parts of steam boilers, have been applied to the design of a boiler of considerable size, which is now nearly completed. This boiler would appear to be the only part of the process which involves any difficulty, and it is hardly fair to expect that it will be in every respect satisfactory or in accordance with calculations, although the evidences in its favor seem to be very strong, and although every detail which enters into it has been the subject of successful experimenting. It is believed, however, that any difficulties which may arise can be corrected and that this process is practicable for approximately such results as have been stated.

A turbine of suitable design has also been produced, and a condensing boiler, with all the auxiliary apparatus necessary for the trial of the process as it might be applied commercially.

With a view to developing a design for a mercury boiler which would produce the vapor with the practicable methods of firing without destructive temperatures in the steel and with a small total amount of mercury in use, it has been necessary to do much experimenting to determine the behavior of mercury under boiler conditions. The first experiments made were with tubes containing solid cores with a small clearance between the core and the tube, and a central hole in the core provided for circulation of the liquid. The apparatus used in this experiment is shown by Fig. 4. A rod was carried downward through the central duct and projected out through a packing as shown. The relative expansion of this rod and of the outer walls of the tube was indicated by a multiplying lever as shown, which afforded an accurate measure of average temperature difference between the outer walls, which constitute the heating surface, and the liquid which was flowing in contact with the rod. This tube was subjected to various heating conditions and curves were plotted which compared rates of vapor flow with temperature difference. Some unexpected results were encountered, and the nature of the action was investigated by boiling mercury in concentric glass tubes having an annular clearance about equivalent to that used in the steel tubes. These experiments showed that to absorb a large amount of heat with a small temperature difference between the heated surface and the liquid, it was necessary to provide for a very free circulation of the liquid so that a large amount of liquid could flow. The size of the central hole had a very positive effect upon the vapor capacity of the tube. Since the mercury does not wet the heating surfaces, the tendency is for the vapor to fill the space between the liquid and the heating surface and thus to prevent heat removal. The way to get effective action in a mercury boiler is to create conditions by which so much liquid will circulate in hot parts that very little vapor is formed until the heated liquid reaches the upper parts of the tubes where the pressure is relieved, and where the heat stored begins to be released in vapor.

Difficulties with temperature differences are only encountered in the hottest parts of the boiler where radiation plays an im-

portant part. With the low rates of heat transference which prevail through a greater part of the surface, extremely narrow spaces can be provided for the circulation of liquid and for the release of the vapor which is formed.

Having obtained, by experiments, data concerning possible rates of heat transference, a boiler was built in which the heating surface was made up of round tubes with concentric cores. The tubes were expanded into a horizontal sheet which formed the bottom of a box, and arrangements were made by which the central ducts in cores always received a supply of liquid. The tubes in this boiler were rather thin, and in experimenting with it, it was found that at the hot end the expanded joints in the tube sheet became loose, the temperature differences imposing strains which exceeded the elastic limit of the metal. This trouble could have been corrected by acetylene-welding these joints, but this would have involved various changes and difficulties, and since trouble was also encountered in making the bolted joints of the box vacuum tight, it was decided to abandon this boiler and build another on an entirely different principle, which had been in the meantime devised and experimented with. The construction of this new boiler is shown by Fig. 7 and the experimental unit used to determine its characteristics is shown by Fig. 6.

This boiler is made up of a number of heating units, each consisting of an upper and a lower header which are connected together by curved flattened tubes. The flattening is to reduce the space which must be filled with liquid mercury without diminishing the surface. The curvature is to prevent mechanical strains through inequal expansion caused by irregular heating. These flattened tubes are connected into the headers by acetylene-welded joints. The tubes are first welded from the inside into channel-shaped pieces; these channels with the set of tubes connecting them are then annealed so as to release all strains incident to the welding. After annealing, they are tested with high-pressure air, suitable clamps being used to confine the air in the channels. If the welded sheets will stand the anneal and the subsequent pressure test, it is assumed that they will be reliable for service, since in service they will be subject to uniform temperature conditions and will be practically free from mechanical strains. These channel pieces are then welded to steel headers so that the whole unit becomes perfectly tight and capable of standing a high pressure. The

headers of these units terminate, as shown, in taper nozzles, which fit into taper holes in the bus header at the bottom and into a vapor chest at the top. A curved liquid duct connects the vapor chest to the bottom header at the hot end so that

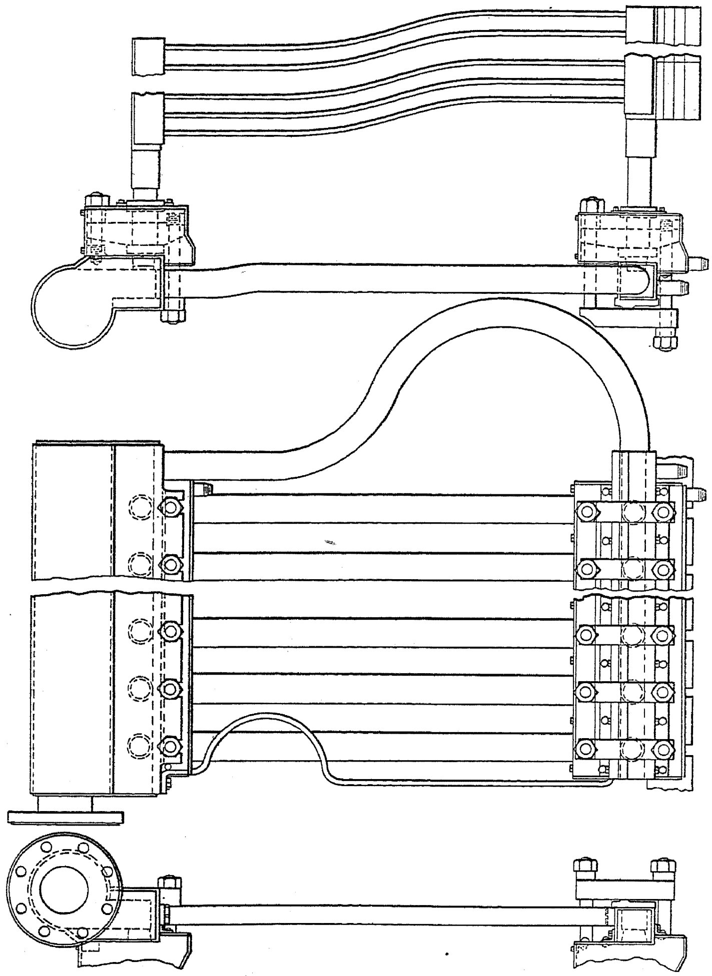


Fig. 7—Assembly of Experimental Mercury Boiler

the heating units which are exposed to the greatest heat receive the most direct supply of liquid. In these hot units, a larger internal space will be allowed than in the units which occupy the cold part of the boiler, so that the colder part will not carry an unnecessary amount of liquid.

If these heating units will remain tight, and the success of experiments indicates that they will, it will be impossible for liquid mercury or vapor to escape except at the joints where

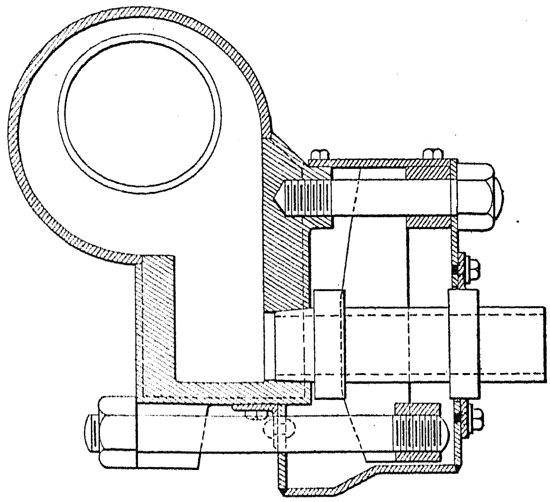


FIG. 8—SECTIONAL VIEW OF UPPER MAIN HEADER, MERCURY BOILER

these headers connect to the bus headers and to the vapor chest, or at the joints through which the vapor is conveyed to the turbine. To guard against loss through leakage in such places, arrangements have been made, as shown in Figs. 8 and 9, by

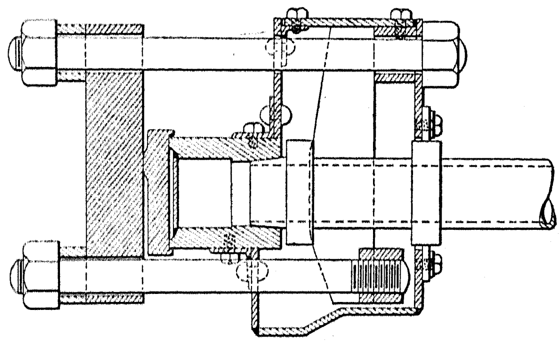


FIG. 9—SECTIONAL VIEW OF LOWER MAIN HEADER, MERCURY BOILER

which the sets of joints at the top and bottom of the boiler are enclosed in boxes which are practically air-tight, the bolts used in tightening these joints extending outside of the boxes in such a manner that a leaky joint can be drawn up. These boxes

are connected by ducts to a condensing cooler in which low pressure is maintained by suction from the base of the stack or from any other sufficiently exhausted place. This suction will maintain within the boxes a pressure lower than any of

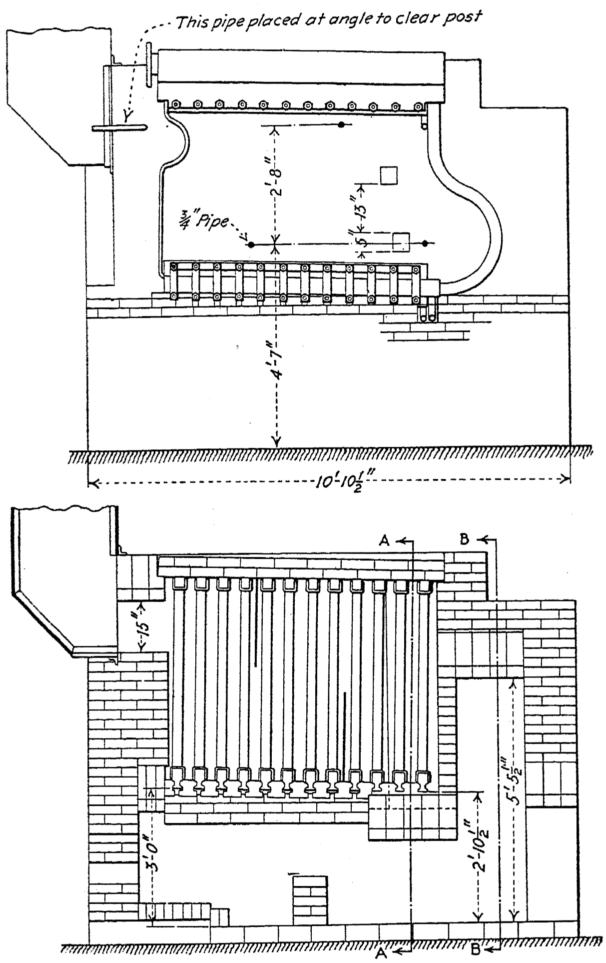


FIG. 10—MERCURY BOILER SETTING

the pressures which surround them, so that there will be a constant indraft of air through such leaks as may exist and a flow of all liquid or vapor which may escape, into the cooler, where it will be carried through passages over water pipes until all

the vapor is condensed and nothing but cool air and gas is discharged. In a similar manner, any joints in the system which might possibly be subject to leakage can be enclosed by boxes and connected to this same cooler. By this means, all possible leakage, except that which may occur in heating units, will be effectively caught.

In case there should be loss of mercury in any of the heating units, means are provided by which such loss can be quickly discovered before any large amount has escaped. The feed of each boiler is so arranged that it is governed automatically by the difference of pressure between the lower header from which

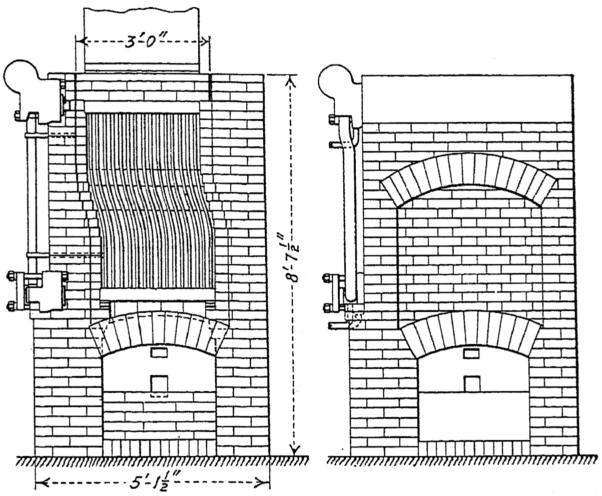


FIG. 10A—SECTIONS OF MERCURY BOILER SETTING SHOWN IN FIG. 10

liquid circulates and the pressure in vapor chest, this being the force necessary to produce sufficient circulation. Back of the valve which admits the feed, there is a reserve chamber, and connecting means are provided by which the level of liquid in this reserve chamber is visible to the fireman. In case loss of this liquid is apparent, the doors would be opened, the fire drawn, and the liquid drained out of the boiler into a receiving tank. The boiler can then be tested with air pressure and the leaky elements can be replaced, the construction being such that any one of these elements can be taken out without disturbing the others.

The arrangements of the turbine have also been improved as

the result of experience. The first turbine arranged was made from an old experimental steam turbine and had many joints which were difficult to keep vacuum tight. The new experimental turbine has only one joint, arranged in a manner which has been experimented with and which will avoid leakage.

The condensing boiler used in the experiment now in preparation is made from a standard high-pressure feed heater having a water space at the top and bottom connected by tubes in the manner customarily used in such devices. This boiler has apparently worked satisfactorily and produced steam from mercury vapor in the manner expected. It is not, however, considered a suitable design for the purpose, since the temperature differences impose a strain on the expanded tube sheets. It is thought that tubes attached at one end with concentric circulation after the manner of the Niclausse boiler will afford the most satisfactory method for such condensers. Since no violent temperature differences will exist, it is believed that these condensing boilers can be made practically free from deterioration and entirely free from leakage.

As has been said, the turbine is provided with a centrifugal packing and is kept sealed by a constant admission of liquid mercury from a suitable head in the condensing boiler. The turbine is also provided with a throttle valve which can be used in governing, and with a bypass valve which allows the vapor to pass directly to the condensing boiler in case the admission to the turbine is shut off.

Proposed Method of Commercial Application

The plan which has been considered for commercially applying this process is to produce a single type of unit suitable for installation in the same floor space occupied by a standard 500-h.p. steam boiler. This unit would be so proportioned that the steam output of the condensing boiler would equal that obtainable from the standard 500 h.p. boiler. For each of these boiler units, a separate turbine and generator would be provided, the nature of this process being such that there is no loss of efficiency involved in such multiplication of generating units.

Since it would never be desirable to operate these mercury-driven generating units alone, the generators could be made either of the induction or synchronous type, completely enclosed, with an air supply from some clean outside source,

Their circuits would run to the main switchboard, they would need no attendance, and the space around them would not have to be kept either cool or clean, although it would generally be possible to get them within an enclosure which would not be exposed to the fire-room dirt. By such means a single set of parts or combinations of a few standard parts could be made to cover a very wide demand, and this would greatly simplify the commercial introduction of such a process.

Without the acetylene welding process, a satisfactory mercury boiler design would be very much more difficult to arrive at. The manufacture of such boilers as are here described would involve a very large amount of acetylene welding, requiring great care and a considerable expense.

The possible cost of the commercial application of such a process has not been carefully studied. It has, however, been roughly estimated that if existing stations were converted to this method, the cost per kilowatt of added power would not exceed the present cost per kilowatt of well-designed steam stations, not including the cost of real estate. Thus this process, if successful, would greatly extend the capacity of existing stations and postpone the building of new stations, the saving would about cover the real estate values, and the gain in fuel economy over that of the best existing plants should be about 45 per cent.

Such a process, with the most efficient oil firing of boilers, ought to give a fuel economy very near to that which is commercially obtainable by Diesel engines, and its mechanical simplicity and freedom from the probability of deterioration should give it a very decided advantage over the Diesel engine. While it is not wise to make definite predictions about anything so radically new, it certainly appears to the writer that this process is worthy of very careful study.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR FISCAL YEAR ENDING APRIL 30, 1913

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its annual report for the fiscal year ending April 30, 1913.

The report includes abstracts from the reports of the various standing and special committees of the Institute; also detailed financial statements showing the condition of the respective Institute funds, receipts and disbursements, assets and liabilities, and other data.

The Board has held 10 meetings during the year; nine at Institute headquarters in New York, and one in Boston during the Annual Convention in June.

The Annual Convention was held in Boston June 24–28, 1912. The total registered attendance was 936, of which 458 were members of the Institute, and 478 were guests, including 198 ladies. The local attendance was 465, and the attendance from outside of the city of Boston and suburbs was 471. Sixty papers were presented at the technical sessions; one session was held jointly with the Illuminating Engineering Society and one with the Society for the Promotion of Engineering Education.

A Midwinter Convention held at Institute headquarters in New York February 26–28, 1913, under the auspices of the Standards Committee, marked a departure from the usual program of Institute meetings of the convention type, being the first convention to be held in New York since the Institute was organized. The meeting was eminently successful from the standpoint of the results accomplished. The data presented in the various papers and discussions will be of great value to the Standards Committee in formulating its revision of the Standardization Rules. Forty-four papers were presented in brief abstract, and the balance of the time was devoted to the discussion. The registered attendance at the convention was 422, of which 179 were from outside of New York and suburbs. The convention closed with a reception and ball at the Hotel Astor, under the auspices of the New York Reception Committee, which was attended by about 300 members and guests, and which was one of the most enjoyable social functions ever given by the Institute.

An Institute meeting, under the auspices of the Schenectady Section, was held in Schenectady on May 17, 1912. Ten technical papers were presented and discussed. The registered attendance was 354 members and guests.

A two-day Institute meeting was held in Pittsburgh on April 18 and 19, 1913, under the auspices of the Pittsburgh Section and the Committee on the Use of Electricity in Mines. Eight papers were presented, and the total attendance was about 300 members.

Upon the request of the Pacific Coast Sections, the Board of Directors

ings, on 3rd and 4th Sept., at which the sub-committee reports were presented to the main body, discussed, and acted upon; and (4) a final Council meeting for the election of officers for the ensuing term, and other formal administrative business.

There were four international sub-committees appointed at Turin in 1911, two of which had been in existence prior to the Turin meeting; these committees were constituted and convened as follows:

Subject	Members, one from	Dates of Meeting	Places of Meeting	Chairman at Berlin
Nomenclature	France Germany Great Britain	March, 1912 March, 1913 September, 1913	Paris Cologne Berlin	Prof. S. P. Thompson
Symbols	Belgium France Germany Great Britain Italy Sweden Switzerland United States	March, 1912 January, 1913 September, 1913	Paris Zürich Berlin	Geh. Dr. K. Strecker
Rating of Electrical Machinery	Belgium France Germany Great Britain Italy Sweden Switzerland United States	May, 1912 January, 1913 September, 1913	Paris Zürich Berlin	Herr Huber-Stockar
Prime movers in connection with Electrical Plant	Austria France Germany Great Britain Italy Norway Spain Sweden Switzerland United States	January, 1913 September, 1913	Zürich Berlin	Dr. H. Zoelly

Nomenclature. The committee on Nomenclature presented an excellent report, which was adopted at the plenary meeting. It contained some 80 electrotechnical terms and definitions, in English and French. The list is too long to be presented in this outline report.

Symbols. The committee on Symbols submitted a report,

in French, which was adopted at the plenary meeting. An English rendering is appended hereto as Appendix A. It will be seen that symbols have been internationally agreed upon for 36 quantities. In cases of nearly half of them, however, (16), agreement could not be reached upon a single symbol; so that for these an alternative is offered. Designating letters, or letter-groups, are provided for 15 electrical units in common use. Standard abbreviations for 29 metric units are also agreed upon. Seven common mathematical symbols are recorded, including both i and j for $\sqrt{-1}$, according to the preference of the writer.

Rating. The committee on Rating was confronted with an exceptionally heavy task. This committee held meetings in Paris in 1912 and in Zurich in 1913. It published its work at those meetings under I. E. C. Publications Nos. 17 and 20. Moreover, General Secretary leMaistre, in I. E. C. Publication 9, of August, 1911, presented the electric machinery rating rules of various countries in a form adapted to comprehensive comparison. Yet in spite of all this preliminary work, it was found that essential issues leading to an international rating for such machinery had not been clearly formulated when the Rating committee met in Berlin. In fact, considering our own committee alone, it is debatable whether a satisfactory technical basis for the rating of electrical machinery had been reached in America prior to the Midwinter Convention of the A. I. E. E., held under the auspices of its Standards Committee, in February, 1913. Consequently, the fact that complete international agreement upon international rating rules was not reached at Berlin need not occasion great surprise.

Just before the Berlin convention of the I. E. C., the U. S. delegation had the advantage of meeting with a Section of the Engineering Standards Committee of Great Britain, which included the British delegation—in London on Aug. 23rd, and again in Berlin, on Aug. 31st. At these meetings the viewpoints of the British and American committees were carefully compared, and adjusted into uniformity on many matters relating to international rating. In effecting this valuable parallelisation of technical views between the two committees, Mr. H. M. Hobart of our committee rendered signal service. The complete conformity between the views of these two national committees on the points of immediate importance in Rating was probably helpful to the I. E. C. International Committee on Rating, in reaching a clear determination of the extent to which

international opinion was in agreement or disagreement, thus paving the way for reaching a final agreement at some future convention, let us hope at San Francisco.

Complete agreement was reached in the I. E. C. Rating Committee on the principle of defining the rating of an electrical machine, so far as thermal behavior is concerned, by a limiting internal or "hottest spot" temperature, as judged by a definitely lower maximum measured temperature attained in the apparatus. A list of such maximum permissible measured temperatures for certain different classes of insulation was agreed on for machines up to four kv. in e.m.f. In order, therefore, to fix upon the international rating, it was only necessary to settle upon an internationally conventional reference-temperature, or circumambient room-temperature. Thus, in the case of impregnated cotton windings, up to four kv., the maximum permissible measured temperature was set at 90 deg. cent. If the international reference temperature, or initial ambient temperature, is taken as say 40 deg. cent., then it follows that the international rating of a machine for continuous service is that output which will finally bring the measured accessible temperature from 40 deg. to 90 deg. cent., or will establish a temperature rise of 50 deg. cent. When working at an actual ambient temperature of 40 deg. cent., the available output would be the same as the international rating. When working at an actual ambient temperature of say 30 deg. cent., the available output would be greater than the international rating, roughly in the ratio $(60 / 50)^{\frac{2}{3}}$ or say 1.13; whereas, when working at an actual ambient temperature of say 50 deg. cent., assuming that the shunt windings of the machine could be operated at so high a temperature, the available output would be less than the international rating, roughly in the ratio $(40/50)^{\frac{2}{3}}$, or the machine would have to be derated about 16 per cent. The advantage of selecting a fairly high international ambient temperature is that the number of localities will be reduced in which, by reason of climatic or locally developed high temperatures, the machine must be derated, or the purchaser warned against taking from it an output equal to its international rating. On the other hand, a fairly low international ambient temperature has the advantage of increasing the international rating of a given machine. That is, a fairly high international ambient temperature makes for safety in applying a load equal to the rating, under summer conditions of service, but tends to diminish the rating.

It is only reasonable to expect that cool countries, lying on the anti-torrid sides of the temperate zones, should desire to set their local or national ambient temperatures correspondingly low, so as to avail themselves of the full benefit of greater available output that their cool climates permit, and that such countries should prefer to have the international ambient temperature set at the same level, so as to have the same rating internationally as locally; even if the machines have frequently to be derated in warmer climates or in engine rooms. So too, it is likewise reasonable to expect that countries subject to warm weather in summer should prefer to have a higher and safer ambient temperature in their local or national standardization rules, in order to avoid frequent derating.

It was found that the great majority of the delegates at the Berlin meeting favored 40 deg. cent. for the ambient temperature of reference, as recommended at the A.I.E.E. midwinter convention, with an international continuous rating for machines of impregnated cotton winding corresponding to 50 deg. cent. rise. But two countries of northern Europe held out for 35 deg. cent. ambient temperature, and therefore a rating based on 55 deg. cent. rise. The delegates from those countries intimated that the 50 deg. cent. rise rating, as recommended for the A. I. E. E. Standardization Rules, was over-conservative, and that a rating based on 55 deg. cent. rise, or nearly 10 per cent more, was safe and proper. The 50-deg. cent.-rise delegates maintained, on the other hand, that the majority of places in the habitable world, where dynamo-electric machinery was operated, were subject to distinctly higher summer ambient temperatures than 35 deg. cent.; so that it was to the interest of international electrical engineering that the international rating should be kept down to a conservative value, in order to minimize the need for summer derating, or precautions against summer overheating under international rating load. No agreement could therefore be reached, and the question of ambient reference temperatures was referred back to the various national committees for further consideration.

On all other points of immediate importance to continuous rating, agreement was reached. Thus, it was admitted that overloads should not be recognized in international rating; *i.e.*, that an international rating for continuous service should specify one maximum permissible output only, and recognize no extras; although it would manifestly lie within the province

of an operating engineer to increase the load above the international rating load in winter time, or under any conditions when the temperatures attained in the machine were well below the specified maximum permissible limits. As soon, therefore, as an international ambient temperature can be agreed upon, international rating of the great majority of machines will thereby be immediately determined. At the present time, however, it is manifest that one and the same machine is subject to different ratings in different countries; or, in other words, that different countries rate their machines in a materially different way.

The report of the I.E.C. Rating Committee, shorn of all specifications as to international ambient temperature, or as to temperature rise for the international rating, was then adopted by the plenary meeting, and will doubtless be issued by the Central office in due course. The list of maximum permissible measured temperatures appears in Appendix B herewith.

Prime Movers. The committee on Prime Movers presented an excellent report dealing mainly with the definitions and nomenclature of hydroelectric installations. This report was also adopted by the plenary meeting, and may be expected to appear later in the official proceedings of the Berlin Meeting.

Annealed Copper Standard. The subject of an International Standard of Annealed Copper was also dealt with at the convention. It will be remembered that the Bureau of Standards, at the request of the A. I. E. E. Standards Committee, took up, in 1910, the computation of a new Standard Copper Wire Table; because recent investigations had shown that the temperature coefficient of resistivity employed in the old Institute Copper Wire Table, computed by the Standards Committee in 1893 from Matthiessen's data, was inaccurate. The Bureau undertook the task,* and made an extensive preliminary investigation of both the resistivity and the resistivity temperature-coefficient of copper wire employed industrially in America. The Bureau found that the mean value of resistivity of good annealed industrial copper in the United States, expressed in terms of the meter-gram, or resistance of a wire one meter long weighing one gram, was, at 20 deg. cent., nearly 0.153 ohm; whereas Matthiessen's standard, as interpreted in the A. I. E. E. TRANS-

*See Circular No. 31 of the Bureau of Standards, "Copper Wire Tables", 2nd Edition, January 1, 1914.

ACTIONS, was represented by a meter-gram of 0.15302 ohm at 20 deg. cent. Consequently, the Bureau accepted the meter-gram of 0.15302 international ohm at 20 deg. cent. as the annealed copper standard, with a temperature-coefficient of 0.00393 per deg. cent. from and at 20 deg. cent. In 1911, the Bureau prepared to issue new wire tables based on the above values. When, however, these data were presented to electrical engineers in Europe, with a view to arriving at an international agreement on the electrical properties of standard annealed copper wire, small differences in data among the various countries revealed themselves. A proposal was then made, in Germany, to adopt a standard copper conductivity as represented by a conductance of 58.00 mhos in an annealed copper wire, at 20 deg. cent., having a length of one meter and a cross-section of one sq. mm. Such a standard corresponds to a meter-gram of 0.15328 ohm at 20 deg. cent. This proposal met with general favor among the National Physical Laboratories, was endorsed by the Bureau of Standards in 1912, approved by the Standards committees of the A. I. E. E. and the A. S. F. T. M. in 1912, recommended by the Rating committee of the I. E. C. in 1912, was finally agreed to, in the French text, by representatives of the National Physical Laboratories in Berlin last September, and was forthwith adopted by the plenary meeting of the I. E. C. A translation into English of the French text appears in Appendix C, herewith.

The adoption of one and the same electrical standard resistivity and temperature-coefficient by the National Laboratories of France, Germany, Great Britain and the United States, as well as by the I. E. C. at Berlin, should ensure complete agreement between the future standard copper-wire tables in all parts of the world, on a conductivity basis substantially the same as Matthiessen's standard. In fact, the differences which have existed during the last few years between the electrical copper standards of the different countries have been unimportant commercially; but have yet been sufficiently large to confuse their numerical comparison. By the action at Berlin, these small numerical discrepancies should in future disappear.

At the Council meeting which followed the plenary meeting, M. Maurice Leblanc, of Paris, was unanimously elected as the President of the I. E. C., to succeed Dr. Budde. It is expected, therefore, that he will preside at the next meeting, at San Francisco, in 1915. Col. Crompton was also unanimously reelected as Honorary Secretary.

An important decision was arrived at in the Council meeting, to the effect that the French text shall henceforward be considered as the text of reference, and that all other texts shall be considered as translations therefrom. French is more familiar to the delegates at large than any other single language, and the difficulty of maintaining two official records side by side in different languages is very great. They can never be brought into such exact equivalence that reference to each, in case of minutious enquiry, will give exactly the same result. Moreover, by having a single reference language, opportunity is opened for adding, in future, other admitted languages of the Commission to the printed records, at owners' risk and expense, thereby extending the literary usefulness of the Commission's publications.

The Spanish delegates invited the Special committees to hold the next meeting in Madrid, and this will probably take place next April. Prof. Chatelain, the Russian delegate, on behalf of his committee, officially invited the I. E. C. to hold a plenary meeting, in 1917, at St. Petersburg.

The German committee, in view of the large amount of work to be done at the meeting, very considerately refrained from overtaxing the delegates with social engagements. The entertainments they offered, were, however, excellent in character, and were greatly appreciated.

The U. S. delegates attending the meeting were President C. O. Mailloux, and Messrs. Bell, Hobart, Kennelly and Sharp. Mr. Mailloux was elected the President of the unofficial meetings, where the duties devolving on the presiding officer are numerous and exacting.

At the plenary meeting, President Mailloux, in pursuance of the invitation given in the first instance by President Dunn at Turin, extended a cordial invitation on the part of the A. I. E. E. and the American Committee, to hold a meeting of the I. E. C., and an International Electrical Congress, at San Francisco, in 1915. This invitation has already been accepted, and we may hope that a large and representative meeting will be held there the year after next.

Respectfully submitted,

A. E. Kennelly
Secretary U. S. Committee.

APPENDIX A

An English rendering of the Report of the Special Committee on Symbols adopted in French at the Berlin plenary meeting of the I. E. C.

General Remarks

By confining oneself to Electrotechnics alone, it would seem possible to standardize symbols. The following rules may serve as a guide to the attainment of this object:

The symbols must be clearly distinguishable one from another when writing with a pen on paper, with chalk on a blackboard, and with a typewriter. In the printed text, it is advisable to use a different type for the symbols from that of the text. It is desirable that in ordinary handwriting, one should not be obliged to add distinctive signs to symbols to specify the type to be employed. It should be possible to spell out the symbols when writing them on the blackboard. Finally, preference should be given to those symbols already in common use. From this it will be seen that it is impossible to make a distinction, in ordinary handwriting, between Roman letters and Italics, and that small roundhand letters, being too difficult to differentiate from the above, cannot be used. It is generally agreed to abandon Gothic type, as requiring too long a time in writing. Finally, many of the Greek capitals are identical with Roman capitals. Taking the above points into account, there remain about one hundred symbols available in Roman, Script and Greek type, of which several are already used for mathematical symbols and which are necessary for the purposes of the electrician. A list of symbols most frequently needed in electrotechnics is appended herewith. Taking into account certain symbols which are occasionally made use of, it is obvious that there will be none left for purely physical or mechanical quantities. Thus one may have, in the same formula, electrotechnical symbols as well as others used in mechanics and physics generally; this is especially the case in equations containing mass, moment of inertia, speed, density, temperature, quantity of heat, etc. The Special Committee on Symbols suggests, therefore, that in such cases, for physical and mechanical quantities, the symbol habitually used by physicists and mechanical engineers should be employed, if this symbol does not already exist in the formula as an electrotechnical symbol. If, on the contrary, it already exists in the formula, it is desirable that it be accompanied by a distinctive sign or that the notation be changed.

Special Propositions

RULES FOR QUANTITIES

(*a*) Instantaneous values of electrical quantities which vary with the time to be represented by small letters. In case of ambiguity, they may be followed by the subscript "t".

(*b*) Virtual or constant values of electrical quantities to be represented by capital letters.

(*c*) Maximum values of periodic electrical and magnetic quantities to be represented by capital letters followed by the subscript "m."

(*d*) In cases where it is desirable to distinguish magnetic quantities (constant or variable) from electric quantities, magnetic quantities should be represented by capital letters of either script, heavy-faced, or other special type. Script letters should not be used except for magnetic quantities.

(*e*) Angles should be represented by small Greek letters.

(*f*) Dimensionless and specific quantities should be represented wherever possible by small Greek letters.

1. Ordinary numerals as exponentials shall exclusively be used to represent powers. (In consequence, it is desirable that the expression $\sin^{-1}x$, $\tan^{-1}x$, employed in certain countries, be expressed by arc sin x, arc tan x.)

2. The comma and the full-stop shall be employed according to the custom of the country, but the separation between any three digits constituting a whole number shall be indicated by a space and not by a full-stop or a comma (1 000 000).

3. For the multiplication of numbers and geometric quantities, indicated by two letters, it is recommended to use the sign $\times$, and the full-stop only when there is no possible ambiguity.

4. To indicate division in a formula, it is recommended that the horizontal bar and the colon be employed. Nevertheless the oblique line may be used when there is no possibility of ambiguity; when necessary, ordinary brackets (), square brackets [], and braces { } may be employed to obtain clearness.

TABLES OF SYMBOLS PROPOSED—I. QUANTITIES

NAME OF QUANTITY	SYMBOL	Symbol recommended for the case in which the principal symbol is unsuitable
1. Length	l	In dimensional equations the capital letters L, M, T, are to be employed.
2. Mass	m	
3. Time	t	
4. Angles	$\alpha, \beta, \gamma \ldots$	
5. Acceleration of gravity	g	
6. Work	A	W
7. Energy	W	U
8. Power*	P	*
9. Efficiency	η	
10. Number of turns in unit of time	n	
11. Temperature centigrade	t	θ ϑ
12. Temperature absolute	T	Θ
13. Period	T	
14. Angular frequency ($2\pi/T$)	ω	
15. Frequency	f	ν **
16. Phase displacement	φ	
17. Electromotive force	E	
18. Current	I	
19. Resistance	R	
20. Resistivity	ρ	
21. Conductance	G	†
22. Quantity of electricity	Q	
23. Electrostatic flux-density	D	
24. Capacity	C	
25. Dielectric constant	ϵ	
26. Self-inductance	L	$\mathcal{L}$ or heavy-faced or special type.
27. Mutual inductance	M	$\mathcal{M}$ or heavy-faced or special type.
28. Reactance	X	$\mathfrak{X}$
29. Impedance	Z	$\mathfrak{Z}$
30. Reluctance	S	$\mathcal{R}$ or heavy-faced or special type.
31. Magnetic flux	Φ	$\mathcal{F}$ or heavy-faced or special type.
32. Magnetic flux-density	B	$\mathcal{B}$ or heavy-faced or special type.
33. Magnetic field	H	$\mathcal{H}$ or heavy-faced or special type.
34. Intensity of magnetization	J	$\mathfrak{J}$ or heavy-faced or special type.
35. Permeability	μ	
36. Susceptibility	κ	

* A symbol for "Power," in the second column, is left "with power" to the Austrian and German committees, to be inserted by them.

** This letter ν may be suppressed later at the instance of the Austrian and German committees.

† A symbol for conductance in the second column is left "with power" to the Austrian and German committees, to be inserted by them.

¶ The German delegate makes reservations as to symbols Nos. 13, 14, 20, 23, 25, 27 to 31, which are not yet accepted in Germany, but does not oppose their adoption by the I. E. C.

II. UNITS. SIGNS FOR NAMES OF UNITS

Sign for names of Electrical Units to be used only after numerical values.

Name of Unit	Sign
1. Ampere	A
2. Volt	V
3. Ohm	*
4. Coulomb	C
5. Joule	J
6. Watt	W
7. Farad	F
8. Henry	H
9. Volt-coulomb	VC
10. Watt-hour	Wh
11. Volt-ampere	VA
12. Ampere-hour	Ah
13. Milliampere	mA
14. Kilowatt	kW
15. Kilovolt-ampere	kVA
16. Kilowatt-hour	kWh

m sign for milli-
k sign for kilo-
μ sign for micro- or micr-
M** sign for mega- or meg-

* One or other of the symbols O and Ω is recommended provisionally to represent the ohm. The symbol Ω should no longer be employed for the megohm.

** Greek capital letter.

III. MATHEMATICAL SYMBOLS AND RULES

Name	Symbol	Symbol recommended for the case in which the principal symbol is unsuitable
Total differential	d	*d*
Partial differential	δ	
Base of Napierian logarithms	e	ϵ
Imaginary $\sqrt{-1}$	i	j
Ratio of circumference to diameter	π	
Summation	Σ	
Summation, integral	$\int$	

IV. MISCELLANEOUS ABBREVIATIONS FOR WEIGHTS AND MEASURES.

Length: m; km; dm; cm; mm; μ = 0.001 mm.
Surface: a; ha; m^2; km^2; dm^2; cm^2; mm^2.
Volume: l; hl; dl; cl; ml; m^3; km^3; dm^3; cm^3; mm^3.
Mass: g; t; kg; dg; cg; mg.

Speed Notation

The Special Committee on Symbols refers the question of finding a suitable name for "speed of rotation expressed in revolutions per minute" to the Special Committee on Nomenclature.

The I. E. C. recommends to the International Electrical Congress of San Francisco the adoption of the name "Siemens" for the practical unit of conductance.

APPENDIX B

Limits of Observable Temperatures Adopted by the I. E. C. in September, 1913

Applicable only to windings for rotating machinery, the terminal pressures of which do not exceed 4000 volts, and to dry transformers with solidly impregnated coils up to 10,000 volts.

Non-impregnated cotton	80	deg.	cent.
Impregnated cotton or paper—general	90	"	"
" " single-layer field coils, stationary or moving)	95	"	"
" " stationary coils solidly impregnated throughout	95	"	"
" " Rotor and stator windings having the slot portion solidly impregnated or molded	95	"	"
Enameled wire (without cotton)	105	"	"
Mica, micanite, asbestos—general	115	"	"
" " single-layer field-coils, stationary or moving	120	"	"
" " stationary coils solidly impregnated or moulded	120	"	"
Windings permanently short-circuited.			
Insulated	100	"	"
Non-insulated	110	"	"
Commutators—slip rings	90	"	"
Bearings	80	"	"

The temperature limits for oil-immersed transformers were not assigned.

APPENDIX C

Translation from the French text adopted at Berlin on the *Annealed Copper Standard.*

REPORT OF THE NATIONAL LABORATORIES CONCERNING AN INTERNATIONAL STANDARD FOR COPPER

I. ANNEALED COPPER

The following values should be taken as normal for annealed standard copper.

1. At 20 deg. cent., the resistance of an annealed copper wire 1 meter long and having a uniform cross-section of 1 sq. mm. is 1/58 ohm = 0.017241...ohm.

2. At 20 deg. cent., the density of annealed copper is 8.89 grams per cu. cm.

3. At 20 deg. cent., the coefficient of variation of resistance with temperature of annealed copper, measured between potential terminals rigidly attached to the wire (constant mass), is 0.00393 = 1/254.5 per deg. cent.

4. Consequently, it follows from (1) and (2) that, at 20 deg. cent., the resistance of an annealed copper wire of uniform cross-section 1 meter long and having a mass of 1 gram is (1/58) × 8.89, or 0.15328...ohm.

II. INDUSTRIAL COPPER

1. The conductivity of annealed copper should be expressed at the temperature of 20 deg. cent. in percentage of that of standard annealed copper, and ordinarily to a precision of 0.1 per cent.

2. The percentage conductivity of annealed industrial copper should be computed in accordance with the following rules:

(*a*) The observation temperature should not differ from 20 deg. cent. by more than 10 deg. cent.

(*b*) The resistance of a wire of industrial copper one meter long and of one sq. mm. cross-section, increases 0.000068 ohm per deg. cent.

(*c*) The resistance of a wire of industrial copper one meter long and of one gm. mass, increases 0.00060 ohm per deg. cent.

(*d*) The density of industrial annealed copper at 20 deg. cent. should be taken as 8.89 gm. per cu. cm.

This value of the density should always be employed in the computation of conductivity in percentage of that of the annealed copper standard.

It follows from the above that if R is the resistance in ohms, at t deg. cent. of a wire having a length of l meters and a mass

of m grams, the resistance of a wire of the same copper one meter long and one sq. mm. cross-section will be

$Rm/(l^2 \times 8.89)$ ohms at t deg. cent. and
$Rm/(l^2 \times 8.89) + 0.000068\ (20 - t)$ ohms at 20 deg. cent.

The percentage conductivity of this copper is thus

$$100 \times \frac{0.01724}{\frac{Rm}{l^2 \times 8.89} + 0.000068\ (20 - t)}$$

Similarly, the resistance of a wire of the same copper one meter long and one gm. in weight is

Rm/l^2 ohms at t deg. cent., and
$Rm/l^2 + 0.00060\ (20 - t)$ ohms at 20 deg. cent.

The percentage conductivity is thus:

$$100 \times \frac{0.1533}{\frac{Rm}{l^2} + 0.00060\ (20 - t)}$$

NOTE 1. The standard values given in (I) are mean values deduced from a large number of tests. Among a number of samples of copper of normal conductivity, the density may differ from normal density up to 0.5 of one per cent, and the temperature coefficient of resistivity may differ from the normal up to one per cent; but between the limits indicated in (II) these deviations will not affect the values of the computed percentage conductivity, if the resulting values are limited to four significant digits.

NOTE 2. The values above stated correspond to the following physical constants for standard annealed copper, all at the temperature of 0 deg. cent.

Density, 8.90 gm. per cu. cm.

Coefficient of linear expansion 0.000017 per deg. cent.

Resistivity, 1.5879* microhm-cm.

Volume resistivity temperature-coefficient 0.00429* per deg. cent. from and at 0 deg. cent.

Resistance temperature coefficient at constant mass, 0.00427 $= 1/234.5$ per deg. cent. from and at 0 deg. cent.

*These two numerical values will probably be changed to 1.5880 and 0.00428 by the National Physical Laboratories. Since reference is made exclusively to the values at 20 deg. cent. when measuring and stating percentage conductivity, these physical constants for 0 deg. cent. are of secondary importance in engineering.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR FISCAL YEAR ENDING APRIL 30, 1913

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its annual report for the fiscal year ending April 30, 1913.

The report includes abstracts from the reports of the various standing and special committees of the Institute; also detailed financial statements showing the condition of the respective Institute funds, receipts and disbursements, assets and liabilities, and other data.

The Board has held 10 meetings during the year; nine at Institute headquarters in New York, and one in Boston during the Annual Convention in June.

The Annual Convention was held in Boston June 24–28, 1912. The total registered attendance was 936, of which 458 were members of the Institute, and 478 were guests, including 198 ladies. The local attendance was 465, and the attendance from outside of the city of Boston and suburbs was 471. Sixty papers were presented at the technical sessions; one session was held jointly with the Illuminating Engineering Society and one with the Society for the Promotion of Engineering Education.

A Midwinter Convention held at Institute headquarters in New York February 26–28, 1913, under the auspices of the Standards Committee, marked a departure from the usual program of Institute meetings of the convention type, being the first convention to be held in New York since the Institute was organized. The meeting was eminently successful from the standpoint of the results accomplished. The data presented in the various papers and discussions will be of great value to the Standards Committee in formulating its revision of the Standardization Rules. Forty-four papers were presented in brief abstract, and the balance of the time was devoted to the discussion. The registered attendance at the convention was 422, of which 179 were from outside of New York and suburbs. The convention closed with a reception and ball at the Hotel Astor, under the auspices of the New York Reception Committee, which was attended by about 300 members and guests, and which was one of the most enjoyable social functions ever given by the Institute.

An Institute meeting, under the auspices of the Schenectady Section, was held in Schenectady on May 17, 1912. Ten technical papers were presented and discussed. The registered attendance was 354 members and guests.

A two-day Institute meeting was held in Pittsburgh on April 18 and 19, 1913, under the auspices of the Pittsburgh Section and the Committee on the Use of Electricity in Mines. Eight papers were presented, and the total attendance was about 300 members.

Upon the request of the Pacific Coast Sections, the Board of Directors

assigned the Pacific Coast Convention this year to the Vancouver Section, and the date has been set for September 9–11, 1913.

During the year President Mershon visited the following Sections: Ithaca, San Francisco, Los Angeles, Philadelphia, Pittsfield, Pittsburgh and Chicago.

On May 21, 1912, constitutional amendments were adopted creating a third grade of membership. As full information regarding these amendments was given to the membership prior to their adoption, it is not necessary again to go into these details in this report. The effect of the amendments during the year has been the transfer of 389 Associates to the grade of Member, and 308 Members to the grade of Fellow, all under the special section of the Constitution, and 9 Members to the grade of Fellow, under the regular provisions of the Constitution.

The constitutional amendments providing for the appointment of the Secretary by the Board of Directors instead of election by the membership were also adopted on May 21, 1912.

The Committee on Organization of the International Electrical Congress, San Francisco, 1915, consisting of about 200 members located in various parts of this country and abroad, was appointed by the President in June, 1912. The duties of this committee are to organize and carry to a successful conclusion the international electrical congress which is to be held in San Francisco in 1915 during the Panama-Pacific Universal Exposition. A brief report of the committee's progress is included herein.

In June, 1912, the Board of Directors passed resolutions agreeing to participate to a limited extent in the proposed International Engineering Congress, which is also to be held in San Francisco during the Panama-Pacific Exposition. This congress is in charge of a committee of management composed of representatives of the principal American engineering societies. The Institute's participation is, however, limited, owing to its obligations in connection with the electrical congress.

On June 27, 1912, the Board authorized the President to enter into reciprocal visiting member arrangements with certain European engineering societies with which negotiations had been pending with such relations in view. The arrangements entitle members of the American Institute of Electrical Engineers, while abroad, to the privileges of membership in the foreign societies interested in the plan, for a period of three months, and foreign members of these societies visiting this country are entitled to the privileges of Institute membership for a like period. The foreign societies which have entered into these relations with the Institute are: The Institution of Electrical Engineers, of England; the Verband Deutscher Elektrotechniker, of Germany; the Societe Internationale des Electriciens, of France; the Associazione Elettrotecnica Italiana, of Italy; the Association Suisse des Electriciens, of Switzerland; and the Koninklijk Instituut van Ingenieurs, of Holland. A considerable number of foreign engineers and Institute members have availed themselves of these privileges since the arrangements were completed.

Foreign relations have been further strengthened during the year by an arrangement entered into by President Mershon on behalf of the Institute with certain foreign engineering societies to exchange abstracts of the papers presented before the societies, for publication in the official organs of the respective societies. This practise was but recently inaug-

urated, and the first foreign abstracts to be published under this arrangements appeared in the April, 1913, PROCEEDINGS.

Upon the suggestion of President Mershon the Electrophysics Committee arranged with Professor Edwin Plimpton Adams, of Princeton University, for the presentation before the Institute of a series of lectures on the subject of radioactivity. Professor Adams, one of the best known authorities on radioactivity in this country, delivered the lectures during the latter part of March and the early part of April, 1913. The widespread interest manifested in the subject by those who attended prompted the Board to authorize the publication of the entire series in the Institute PROCEEDINGS in order that the entire membership might have this opportunity of obtaining practical and theoretical knowledge of this interesting and important subject. These lectures will also be reprinted in pamphlet form for sale at a nominal price.

Two new technical committees have been created during the year; namely, the Committee on the Use of Electricity in Mines, appointed in December, 1912, and the Committee on the Use of Electricity in Marine Work, appointed in April, 1913, both of which will open to the Institute new and important fields of usefulness and activity.

The following brief statements, consisting principally of abstracts from the reports of various Institute committees, give an outline of the results accomplished. A large amount of work has also been done by temporary committees, appointed during the year for some specific purpose; also by delegates of the Institute to meetings of other technical organizations, and by representatives upon various boards, commissions, and other local and national bodies.

In the limited amount of space available it is not possible to give more than an outline of the activities of the Institute, but this is sufficient to indicate the wide scope, and the constantly increasing amount, of the useful work that is being carried on by the American Institute of Electrical Engineers through its members, committees and officers.

Sections Committee.—In accordance with the custom that has been followed for a number of years, the activities of the Sections and Branches are summarized briefly in tabular form, as follows:

	Year Ending					
	May 1 1908	May 1 1909	May 1 1910	May 1 1911	May 1 1912	May 1 1913
SECTIONS						
Number of Sections.........	21	24	25	25	28	29
Number of Section meetings held.........	141	169	187	208	231	244
Total attendance	7,476	16,427	16,694	15,243	19.800	22,825
BRANCHES						
Number of Branches....	22	26	31	36	42	47
Number of Branch meetings held.....	143	198	237	255	281	357
Attendance.....	4,128	8,443	10,255	10,714	10,255	11,808

No mere table can show the real influence of the Sections of the Institute. In a larger and larger sense the Sections are becoming the Institute. Primarily the Sections are having a nationalizing influence. While it is undoubtedly true that the Sections have tended to reduce general interest in the regular monthly meetings in New York, at the same time an interest in local Section meetings has been stimulated that in the aggregate has made for a vastly increased interest in the Institute. Individual Section meetings are now taking on a character that would have done credit to the general Institute meetings of a few years back. Opportunities which formerly were available only to those so situated that they could attend the New York meetings are now open to those around 29 different centers.

Another gratifying result is the rapid increase in the number of University Branches. The principal benefit that is derived from these Branches is to bring our Institute to the attention of those who in a few years will be ready to take their active part in the electrical engineering profession.

The Sections Committee reports a very satisfactory year.

Committee on Sections Participation in Conduct of Institute Affairs.—The work of this committee is not sufficiently advanced to permit the submission of a complete report, for the reason that not all of the Sections have replied to the communication sent them by the committee, and the committee has not felt itself in a position to formulate conclusions even of a preliminary nature until a fuller response is received from the Sections.

As the resolution under which this committee was appointed was drawn in response to a resolution adopted at the Sections Conference at the Boston Convention in June, 1912, it was the sense of the committee that suggestions or recommendations on the matters coming within its scope should be requested of the Sections. In answer to the committee's invitation for comments replies have been received from about one-third of the Sections. In nearly all of these communications the Sections concerned have brought forward interesting and profitable suggestions relative to the work and activities of the Sections as Sections, but, in the main, no comments have been received indicating a desire for a change from the present system of the conduct of Institute affairs or bearing directly on the question of the participation of the Sections therein.

A formal report will be presented during the Annual Convention.

Meetings and Papers Committee. During the year the committee has arranged for six regular meetings in New York, a series of five lectures on radioactivity, a midwinter convention, and a meeting at Pittsburgh. It has been the policy of the Meetings and Papers Committee this year to assign each of the regular meetings of the Institute to one of the technical committees, which has obtained the papers and under whose auspices the meeting has been conducted. The chairman of the technical committee supplying the program for any meeting has presided at the technical session of such meeting.

During the present year the 60-day rule in regard to papers has also been adopted, under which every paper to be presented before the Institute must be in the hands of the Meetings and Papers Committee at least 60 days prior to the date of the meeting at which it is to be presented, and no assignment of a paper to any meeting is made until the manuscript is in the committee's hands. The operation of this rule has worked out very successfully, both in permitting the committee to give more con-

sideration to the papers presented and in permitting publication of the papers sufficiently in advance of the meetings to facilitate valuable discussion.

At the 1912 annual convention held in Boston 60 papers were presented, and joint sessions were held with the Society for the Promotion of Engineering Education and the Illuminating Engineering Society. This large number of papers required the holding of parallel sessions each day of the convention and afforded rather limited time for the discussions. Preparations are now under way for the 1913 annual convention to be held in Cooperstown, N. Y., June 23–27, and it is the intention to limit the technical program to 20 or 25 papers. According to the committee's plans, those papers which cannot be included in the convention program will be held over until fall in order to supply the incoming committee with papers for use at the first two or three fall meetings before the new committee has had opportunity to get actively at work.

New York Reception Committee.—The New York Reception Committee has arranged for the smokers which have been held at Institute headquarters in connection with the monthly meetings. These smokers have been supported entirely by voluntary contributions from members residing in and near New York.

The committee arranged for the reception and ball held at the close of the Midwinter Convention in New York in the latter part of February, and maintained in the Engineering Societies Building during the convention a bureau of general information for out-of-town members and guests.

In co-operation with the local committees of the American Society of Mechanical Engineers and the American Institute of Mining Engineers the committee participated in the presentation before the three societies on April 4 of a demonstration of Edison talking moving pictures.

Railway Committee.—The Railway Committee has prepared for presentation at the Annual Meeting in May, 1913, two papers: One on *2400-Volt Railway Electrification*, by H. M. Hobart, and the other on *Trunk Line Electrification*, by Charles P. Kahler. Invitations for oral and written discussions of these papers, together with printed copies of the papers themselves, have been sent to various members and to foreign engineers interested in railway operation.

Educational Committee.—The Educational Committee, following the suggestion of last year's committee, directed attention again this year to the field of industrial education, and at a meeting of the committee held in January the subject was divided among the members for study and report. The result of the committee's work will be the presentation of a number of papers on various phases of industrial education at the Annual Convention.

On January 10, 1913, the Board of Directors authorized the committee to appoint a representative to attend the first annual convention of the National Association of Corporation Schools, held in New York on January 24. Professor W. I. Slichter was appointed and represented the Institute at the convention. The association is composed of corporations and companies which are engaged in or interested in the education of their employees. Its objects are to collect and compile records of successful and unsuccessful methods of educating employees and to distribute this

information to members of the association. Although it does not seem possible nor at the present time advisable for the Institute to take any official part in the movement, it is believed that the Institute, through the Educational Committee, can assist and thus do a public service by keeping the membership advised of the work of the association.

High-Tension Transmission Committee.—The December, 1912, Institute meeting in New York was held under the auspices of the High-Tension Transmission Committee. At this meeting two papers were presented on the subject of "Testing of High-Tension Line Insulators." The committee has been studying this subject since that meeting, and is preparing for a further discussion at the coming Annual Convention, with the idea of later recommending, if possible, a model or a general specification for the testing of such insulators. The committee has secured two tentative specifications; one representative of the point of view of the manufacturer of insulators; the other the point of view of the scientist and expert tester. It is proposed that the High-Tension Transmission Committee, taking the point of view of the practical engineer, prepare from these a single specification which may be submitted to the Institute for approval.

The committee has prepared and is about to send out a list of questions bearing on engineering matters of special interest in connection with high-tension power transmission systems, to the managers of plants operating at voltages of 25,000 or higher. It is hoped that from the replies to these questions a great deal of valuable information may be gained as to the present practise in such systems. This plan, which is similar to that successfully tried 10 years ago by President Mershon, who was then chairman of the High-Tension Transmission Committee, is now taken up at his suggestion.

It is not expected that either the high-tension testing specification or the collection of engineering data will be completed during the life of the present committee, but it is hoped that the work will be carried on to a successful conclusion by the succeeding committee which takes office on August 1 next.

Electric Lighting Committee.—The Electric Lighting Committee has not held any meetings, owing to the wide geographical distribution of its membership, and the work has therefore been carried on through correspondence. The committee originally arranged for a meeting to be held in February, but it was postponed on account of its proximity to the Mid-winter Convention, and no later date could be fixed upon for this meeting. The committee's work has therefore consisted in obtaining papers for presentation before the Annual Convention, and three paper on subjects of timely interest in the electric lighting field have been submitted for this purpose.

Industrial Power Committee.—The Industrial Power Committee has confined its work entirely to arranging for papers and the discussion of these papers at the regular Institute meetings, and in giving assistance and suggestions to Sections regarding papers for Section meetings. In the selection of papers special care has been taken to select papers of general interest which would evoke considerable discussion. The papers arranged for have covered a fairly wide range of subjects so as to make the complete program for the year representative of the variety of problems

encountered in industrial engineering. In addition to papers already presented the committee has provided five papers for the Annual Convention.

Telegraphy and Telephony Committee.—The Telegraphy and Telephony Committee held no meetings during the year, the widely scattered membership of the committee making a full meeting difficult. Arrangements have been perfected which will result in the presentation of a number of papers on telegraphy and telephony at the Annual Convention. There has developed among Institute members a disposition to consult the Telegraphy and Telephony Committee on special problems. None of these has been sufficiently important to require that it be presented to the committee in general, but the tendency is here reported upon as of interest in indicating a new form of usefulness which an Institute committee might develop. The chairman has answered such inquiries to the best of his ability.

Electrochemical Committee.—The work of the Electrochemical Committee for the year has been confined to attempts to secure suitable papers on electrochemical subjects, treated from an engineering viewpoint. Owing to the scattered geographical distribution of its members, no meetings have been held, and the work has been carried on through correspondence. It was decided not to have a meeting devoted to electrochemistry, but to obtain a few papers for the Annual Convention. Two papers have been promised and will be available in time for advance printing.

Power Station Committee.—The Power Station Committee obtained the paper on *High-Speed Turbo-Alternators—Designs and Limitations*, which is believed to be one of the best and most useful papers presented before the Institute during the past year. In addition to this a paper is to be presented under the auspices of this committee at the Annual Convention, on *Standardization of Method for Determining and Comparing Power Costs in Steam Plants*. It is hoped that the latter paper will bring out a discussion that will be of value to the Standards Committee in the revision of the standardization rules, with special reference to a method of determining and comparing costs of power.

Electrophysics Committee.—The efforts of the Electrophysics Committee have been exeited in three directions: 1. To the securing of papers on subjects more particularly pertaining to the physical theory underlying electrical engineering. 2. To the arrangement of a series of lectures on radioactivity. 3. To the stimulation of interest in experimental research.

The Institute meeting in New York on March 14, 1913, was held under the auspices of this committee, and two important papers were presented.

The committee arranged the series of lectures on "Radioactivity" given by Professor Edwin Plimpton Adams of Princeton University, in the latter part of March and early April.

The committee has, through correspondence, made several efforts to secure a list of subjects for research and of questions whose answers are needed in the pursuit of various branches of the profession. So far the results from these attempts have not been numerous, but it is believed that such results could not be expected to follow immediately, and it is hoped

that the succeeding committee will find that a promising start has been made in this direction.

Committee on the Use of Electricity in Mines. The Committee on the Use of Electricity in Mines, in co-operation with the Pittsburgh Section, held a very successful meeting in Pittsburgh on April 18 and 19, devoted largely to the subject of central station power for mining purposes. The attendance at the meeting was about 300, and there was a good general discussion of the papers presented. Following this meeting the committee held an informal session at which it was decided to co-operate with the Pittsburgh, Chicago and Philadelphia Sections in the preparation of papers pertaining to electrical mining, and to assist in bringing out a full discussion. Nothing further is contemplated at the present time except that the committee will tabulate a list of electrical mining men who might be interested in the activities of the Institute, with the view to communicating with them through the various Sections, and if possible enlisting them in the work. This phase of the work will be undertaken by the Sections themselves with the co-operation of the Membership Committee.

Editing Committee. Twelve numbers of the PROCEEDINGS have been published under the auspices of the Editing Committee since April 30, 1912, the total number of pages published during this period being 3460, of which 473 pages comprise Section I, and 2987 pages Section II. Owing to the increasing amount of material to be published in our TRANSACTIONS, the Editing Committee determined to reduce the bulk and cost of the volumes by printing the TRANSACTIONS on a thinner paper of better quality, which will permit the publishing of the volume for 1912 in two parts, although it contains approximately the same number of pages for which three parts were required the previous year, printed on the heavier paper. All of the discussions at the regular Institute meetings and at the Sections which have been printed have been edited and published under the supervision of the Editing Committee.

Indexing Transactions Committee. The Indexing Transactions Committee has completed the work of classifying the synopses of the papers and the arranging and editing of the cards. At the present time the whole manuscript for the two volumes of the index, one covering the period 1884 to 1900, and the other 1901 to 1910 inclusive, is in the press.

Standards Committee. The Standards Committee has under consideration a revision of the Standardization Rules, and has appointed a sub-committee to collect material for such revision. It was considered desirable to present to the Institute, for discussion, papers from engineers in construction and installation, indicating directions in which modifications of the existing rules might well be made. The Board of Directors authorized on August 8, 1912, the holding of a Midwinter Convention in New York. This convention was assigned by the Meetings and Papers Committee to be held on February 26, 27 and 28, 1913, under the auspices of the Standards Committee. Forty-four papers were prepared for this convention, forty-two of which were printed in advance in the February PROCEEDINGS, and two in the March PROCEEDINGS. Herr Leo Schuler attended the convention as a delegate from the Verband Deutscher Elektrotechniker.

In November, 1912, the American Society of Mechanical Engineers appointed a special committee to confer with the Standards Committee, and a joint meeting of the two committees was held on December 13, 1912, with Mr. H. G. Stott of the A. S. M. E. committee as chairman. Certain resolutions were passed by the joint committees in favor of the adoption of the "myriawatt" as a unit of power. The report of this joint meeting appears on pages 59 and 60 of the February, 1913, PROCEEDINGS. The report received the approval of the governing boards of both societies.

Meetings of the committee have been held at monthly intervals during the year, except during June, July and August.

Reciprocal relations have been entered into to some extent between this committee and the standards committees of the A. S. M. E., the A. S. F. T. M., and the I. E. S., under a resolution on the subject adopted by the Board of Directors on April 9, 1913.

Code Committee.—The work of the Code Committee for the year 1912–1913 has been accomplished without a general meeting of the whole committee, the matters coming before it being of such a nature as to permit their disposal by correspondence.

The important work of the Code Committee really consisted in its representation at the biennial meeting of the National Board of Fire Underwriters, in order to assist in presenting data for the purpose of making the mandatory grounding of secondaries an accepted rule by the Board of Fire Underwriters. The chairman of the committee attended the four-day conference held in New York on March 24–27, and reports that the mandatory grounding of secondaries up to 150 volts, and the permissible grounding of secondaries up to 250 volts, has been approved by the National Board of Fire Underwriters, and the mandatory rule will be printed in the 1913 code.

Law Committee.—The Law Committee, in its advisory capacity, has during the year presented its views upon the following questions which have been submitted to it: The question as to the date upon which the total membership of the Institute should be taken in estimating the number of ballots required to adopt amendments; amendments to the By-laws with reference to the question of transfers under the special section of the Constitution; interpretation of the Constitution and By-laws with reference to certifications under the special section, including a proposed amendment to the special section of the By-laws; modification of the Wheeler Deed of Gift to the Institute library; report on the status of the Secretary of the Institute after August 1, 1912; the question as to the power of the Board of Directors to refuse to transfer applicants under the special section of the Constitution; the form of election ballot to be printed.

Library Committee.—In accordance with Section 24 of the By-Laws of the Institute, we beg leave to submit herewith our annual report for the year ending April 30, 1913, showing the state of the library and including the names of all donors to it.

During the year the erection of two ornamental metal book-cases, one on each side of the main entrance to the library on the 13th floor, has been completed. These are intended to serve for storage and display of a large portion of the Latimer-Clark collection of books which was donated to the Institute by Dr. Schuyler Skaats Wheeler.

As a result of the combined efforts of the Library Committees of the three founder societies, and of the Joint Conference Committee, an organization for the administration of the library by a library board subject to the direction of the Board of Trustees of the United Engineering Society, has been effected, with the approval of the Boards of Directors of these founder societies. The character of the organization is set forth in the following extract from the By-Laws of the United Engineering Society, which went into effect in November, 1912.

Library and Educational Work

74. The Board of Trustees shall maintain and conduct a Free Public Engineering Library, subject to such regulations as it may from time to time determine.

75. The library shall be conducted by a Library Board, subject to the direction of the Board of Trustees.

76. The Library Board shall consist of sixteen members, composed as follows:

Four members designated by each of the three Founder Societies.

The Secretary of each of the three Founder Societies.

The Librarian, who shall also be the Secretary of the Board.

One member shall be designated by each Founder Society each year to serve four years.

Any vacancy occurring among the appointed members shall be filled by the corresponding Founder Society for the unexpired term.

77. Regular meetings of the Library Board shall be held on the first Thursday of February, May, September and December of each year. Special meetings may be called at the option of the Chairman, on not less than seven days' notice, and must be called by the Chairman on the written request of seven or more members. A quorum shall consist of not less than seven members, of whom at least four shall be appointed members, including at least one such member from each of the Founder Societies.

78. At its first regular meeting in each calendar year the Library Board shall elect one of its members to be Chairman for a period of one year or until his successor is elected. At the same meeting the Library Board shall elect from its own members an Executive Committee to consist of an equal number of members from each of the Founder Societies, to serve for one year. The Chairman of the Library Board shall be ex-officio a member and Chairman of the Executive Committee. The Librarian shall be ex-officio Secretaryof the Executive Committee, but shall have no vote.

79. If less than a quorum be present at a meeting of the Library Board the members present may adjourn the meeting to a day fixed.

80. The Library Board shall have authority

To originate, revise and approve rules for the administration of the library.

To prepare and forward to the Board of Trustees, requisitions for furniture and other supplies.

To appoint and fix salaries of employees in the library, subject to the approval of the Board of Trustees.

To revise and approve lists of publications authorized by the Founder Societies for purchase, with a view of avoiding unnecessary duplication.

To direct the purchase on account of the United Engineering Society of publications not on file in the library, under such regulations and within such limits as the Board of Trustees may prescribe.

To receive and administer bequests and gifts to the Library of the United Engineering Society.

81. At the end of each calendar year the Library Board shall present, to the Board of Trustees and to the Founder Societies, a full report of its acts during the past year, including a financial statement of its receipts and disbursements and its recommendations for the coming year as to policy and finance. This report shall state the recommendation of the Library Board as to the sum of money which each Founder Society should expend during the coming year for the purchase of books for the library of that society; and as to the sum which the United Engineering Society should expend for the purchase of books or periodicals for the Library of the United Engineering Society; and as to the sum each society should contribute toward the cost of administration.

82. A regular meeting of the Executive Committee shall be held on the first Wednesday of each month except July and August. Special meetings may be called by the Chair-

man. A majority of the members shall constitute a quorum, but a less number than a quorum may adjourn the meeting to a day fixed. The Secretary of any of the Founder Societies may be present at any meeting and shall have the same right as members to be heard, but shall have no vote. Notice of each called and adjourned meeting shall be sent to each such Secretary.

83. The Executive Committee shall be the representative of the Library Board and shall execute the instructions of the Library Board, and whenever necessary shall take any action for which the Library Board has authority, reporting such action for approval to the Library Board at the next following meeting of said Board.

84. The Librarian shall be appointed by the Board of Trustees from a list of names submitted by the Library Board.

85. The Librarian shall be the Executive of the Library Board and of its Executive Committee, and, subject to the direction of said Board and Committee, shall have charge of the library.

86. The Librarian shall be a member and the Secretary of the Library Board, and the Secretary, but not a member, of the Executive Committee.

87. At each meeting of the Library Board the Librarian shall submit a written report containing his recommendations for the purchase of books and supplies, and for any changes in service or in the work of the library.

88. The Board of Trustees shall also co-operate with the Founder or Associate Societies in giving public lectures on engineering and scientific subjects and in arranging for the conduct of educational and research work as from time to time may be deemed advisable.

The Library Board was organized on February 6, 1913, with Dr. Leonard Waldo as Chairman.

Statistical information concerning the library and its use during the year, including a list of donors, is given in the following tables:

Donors

May 1, 1912—April 30, 1913

ADAMS, E. D.	8
AMERICAN ELECTRIC RAILWAY ASSOCIATION	4
AMERICAN ELECTROCHEMICAL SOCIETY	1
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	3
AMERICAN JOURNAL OF SCIENCE	2
AMERICAN RAILWAY ASSOCIATION	1
AMERICAN SCHOOL OF CORRESPONDENCE	4
AMERICAN TELEPHONE & TELEGRAPH COMPANY	1
ARNOLD, BION J.	12
MR. BISSING	1
BENEDICT, V. L.	1
P. BLAKISTON'S SON & COMPANY	1
BOSTON TRANSIT COMPANY	1
BOSTON WIRE DEPARTMENT	1
BUCHANAN, J. Y.	2
BYLLESBY, H. M.	1
CALDWELL, EDWARD	1
CARNEGIE INSTITUTION OF WASHINGTON	2
CENTRAL STATION PUBLISHING COMPANY	1
CHANDLER, C. de F.	2
CONGRESO CIENTIFICO	1
CUSHING, H. C.	1
DEPARTMENT OF AGRICULTURE	1
DEPARTMENT OF LABOR	2
DEPARTMENT OF TERRESTRIAL MAGNETISM	2
DUNOD & PINAT, PARIS	1
EICKEL, E.	1

ELECTRICAL RAILWAY JOURNAL	1
ENGINEERING NEWS COMPANY	7
FORTSCHRITTE DER PHYSIK	1
FOWLE, F. F	5
GATI, M. B	1
GAUTHIER, VILLARS	3
GEROSA, E	1
HANSEN, L	1
HEIMAN S. & SOHN	1
HERING	1
HERMAN ET FILS, A	2
HOLMGREN, T	2
INDIA RUBBER JOURNAL COMPANY	1
INSTITUTION OF ENGINEERS AND SHIPBUILDERS, SCOTLAND	1
INTERNATIONAL ELECTRIC PROTECTION COMPANY	1
INTERNATIONAL ELECTRICAL CONGRESS, ST. LOUIS	1
IOWA ELECTRICAL ASSOCIATION	1
IOWA ENGINEERING SOCIETY	1
ISOLATED PLANT PUBLISHING COMPANY	1
KANSAS, GAS WATER AND STREET RAILWAY ASSOCIATION	1
KENNELLY, A. E	6
KAHN, H. R	1
LAUFFER, C. A	1
LIBRARY OF CONGRESS	1
LIPPINCOTT COMPANY	2
LOUBAT & CIE	1
MACMILLAN COMPANY	2
MAILLOUX, C. O	1
MARTIN, T. C	10
MARYLAND PUBLIC SERVICE COMMISSION	1
MASSACHUSETTS GAS & ELECTRIC LIGHT ASSOCIATION	1
MASSACHUSETTS INSTITUTE TECHNOLOGY	1
MAVER, WILLIAM, JR	6
MCALLISTER, A. S	1
MCGRAW-HILL BOOK COMPANY	2
MCPHERSON, L. G	1
MERSHON, RALPH D	1
MOIS SCIENTIFIQUE ET INDUSTRIAL	1
MOURLON, CHAS	1
MUNICIPAL ENGINEERING COMPANY	1
MURALT & COMPANY	1
NACHOD SIGNAL COMPANY	1
NATIONAL ELECTRIC LIGHT ASSOCIATION	3
NATIONAL BOARD OF FIRE UNDERWRITERS	1
NATIONAL CIVIC FEDERATION	1
NATIONAL ELECTRIC LIGHT COMPANY	1
NATIONAL FIRE PROTECTION ASSOCIATION	4
NATIONAL WATERWAYS COMMISSION	1
NEW ENGLAND WATER WORKS ASSOCIATION	2
NEW JERSEY BOARD RAILROAD COMMISSION	2
NEW ORLEANS SEWERAGE AND WATER BOARD	1

NEW YORK BOARD OF FIRE UNDERWRITERS	1
NEW YORK BOARD OF WATER SUPPLY	1
NEW YORK ELECTRICAL SOCIETY	1
NEW YORK STATE DEPARTMENT OF LABOR	3
NEW YORK STATE PUBLIC SERVICE COMMISSION	3
NOEGGERATH, J. E.	1
NORTH EAST COAST INSTITUTION OF ENGINEERS AND SHIPBUILDERS	1
NORTH EAST COAST POWER SYSTEM COMPANY	1
OSTERREICHISCHER BETON VEREIN	1
OURO PRETO SCHOOL OF MINES	9
PAINT MANUFACTURERS ASSOCIATION OF THE U. S.	1
PHILADELPHIA DEPT. OF PUBLIC WORKS	1
PIERCE, A. L.	2
PLATTHER, WM.	1
POLYTECHNIC INSTITUTE OF BROOKLYN	1
PRADO, H. C.	1
RAILWAY AGE GAZETTE	1
RAILWAY SIGNAL ASSOCIATION	1
RENSSELAER POLYTECHNIC INSTITUTE	1
SCHOEN, A. M.	1
SCOTT, FORESMAN & COMPANY	1
SEVER, G. F.	1
SIEMEN & HALSKE	1
SOCIETY OF CHEMICAL INDUSTRY	2
SOCIETY FOR THE PROMOTION OF ENGINEERING EDUCATION	1
SOUTH WALES INSTITUTE OF ENGINEERS	1
SOUTHWESTERN ELECTRICAL & GAS ASSOCIATION	4
SPERRY, E. A.	1
TELEPHONE PIONEERS OF AMERICA	1
THOMPSON, SLASON	1
TRANSVAAL INSTITUTION OF MECHANICAL ENGINEERS	1
TREASURY CONSTRUCTION SOCIETY	1
U. S. BUREAU OF STANDARDS	2
U. S. NATIONAL MUSEUM	1
U. S. WAR DEPARTMENT	2
UNIVERSITY OF LONDON PRESS	1
UNIVERSITY OF MINNESOTA	1
UNIVERSITY OF PITTSBURGH	1
VAN NOSTRAND, D. COMPANY	6
WARE, H. E.	1
WEAVER, W. D.	2
WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY	1
WHITEHEAD, J. B.	2
WILEY, J. & SONS	1
ZEHNDER L.	4
ZEITSCHRIFT FUR BELEUCHTUNGSWESEN	1
DONOR UNKNOWN	4
OLD MATERIAL	26
	258

Exchanges	172	
Purchases and old material accessioned	399	
		571
Total accessions		829

The following tabulation gives the state of the accounts from which the Library Committee is entitled to draw:

DONATIONS (GENERAL LIBRARY FUND)

DR.		CR.	
Balance May 1, 1912	$271.15		
Interest	6.80	Unexpended	$277.95
	$277.95		$277.95

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications)

Balance May 1, 1912	$78.55	Expended	$46.00
Interest	45.00	Unexpended	77.55
	$123.55		$123.55

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904, FUND

(Proceeds available for the purchase of non-American international electrical literature)

Invested in New York City 4½% Bonds	$2268.00
Additions to the Fund	76.85
Total Fund	$2344.85

Balance on hand May 1, 1912	$309.12	Expended	$3.88
Interest	90.00	Unexpended	$395.24
	$399.12		$399.12

WEAVER DONATION

(Available for the purchase of early electrical literature)

Balance May 1, 1912	$6.69	Unexpended	$6.69

INSTITUTE APPROPRIATION ACCOUNT

Appropriation for the year	$4500.00	Salary (one-third) of librarian, assistants, cataloguer and desk attendant, May 1, 1912 to May 1, 1913	$2704.93
		One-third running expenses of library, May 1, 1912 to May 1, 1913	153.76
		Books	1105.44
		Subscriptions	151.63
		Insurance	71.48
		Binding	352.46
		Miscellaneous	18.08
			$4557.78

STATISTICS OF LIBRARY MAY 1, 1913.

Source	Volumes	Pamphlets	Valuation
Report of May 1, 1913	16,141	1512	$32,660
Purchase	357	16	1,051.75
Gifts and exchanges	327	112	682.00
Old material accessioned	14	12	31.00
Unknown	4		8.00
	16,843	1652	$34,432.75

In the following table are given the figures for the total valuation of the Library property:

Books	$34,432.75
Stacks	1,761.05
Furniture, catalogues, cases, etc.	376.00
	$36,569.80

LIBRARY ATTENDANCE

		Day	Night	Total
May,	1912	641	269	910
June,	"	519	213	732
July,	"	638	closed	638
August,	"	561	"	561
September,	"	585	146	731
October,	"	566	204	770
November,	"	669	215	884
December,	"	713	214	927
January	1913	640	247	887
February	"	674	232	906
March,	"	655	275	930
April,	"	806	265	1071
Total May 1912-April 1913		7667	2280	9947
Total May 1911- April 1912		8601	2747	11348

The income from the C. O. Mailloux Fund, amounting to $1000, has again been used to maintain the four important sets which were presented to the library by Mr. Mailloux.

Respectfully submitted,

FREDERICK BEDELL
PHILANDER BETTS
DUGALD C. JACKSON
MALCOLM MAC LAREN
SAMUEL SHELDON, *chairman.*

Public Policy Committee.—The Public Policy Committee has not been called upon, up to the present time, to initiate policies, but has acted in a consulting capacity, considering only such matters as have been referred to it by the proper authorities from time to time.

During the past year the committee has held four meetings, at which the following matters have been considered and reports made thereon: Desirability of opposing injurious legislation regarding the American

patent system; proper attitude of Institute Sections towards local civic matters; invitation from Secretary of the Interior Fisher to attend a conference at Washington between government officials and California representatives to consider proper governmental restrictions on hydro-electric developments wholly or partly on land in federal reservations; form of credentials for Institute delegates to other bodies; desirability of organizing a national electrolysis committee; proposed rules and regulations for service supplied by electric companies; desirability of appointing a delegate to Advisory Board of National Conservation Congress; proposed by-law providing for co-operation of Standards Committee with similar committees of other national organizations; policy of the Institute towards proposed legislation in New York State contemplating the licensing of engineers.

Patent Committee.—The Patent Committee, while it has held no meetings, has kept in touch with the President of the Institute by correspondence and telegraph, and through its efforts has, it is believed, exerted effectual influence in preventing adverse patent legislation at Washington.

There has been considerable discussion regarding the advisability of changing the patent laws of the country, and there was introduced during the last Congress a bill known as the Oldfield Bill, intended to rectify some of the present defects of the Patent Laws, as applied to patents pending in the Patent Office and after they are issued. This bill, while meritorious in many particulars, had certain fundamental weaknesses which, had the bill been passed, would have destroyed many of the advantages which it was intended to secure, and, in addition, would have placed inventors in many respects at a greater disadvantage than they now are.

For this reason it seemed best to the members of the committee to oppose the bill and suggest that an independent, unbiased commission be appointed by the President of the United States to analyze the entire patent situation and make recommendations regarding changes in the patent laws. Accordingly, the committee recommended for passage by the Board of Directors certain resolutions, which had been suggested by President Mershon, urging the Congress of the United States to provide for such a commission, and to hold in abeyance all proposed legislation affecting the patent system until such time as the commission shall have had opportunity to hold hearings and study the situation. These resolutions were adopted by the Board of Directors on November 8, 1912, and copies were forwarded to each senator and representative of the United States who was a member of the Senate or House Committee on Patents.

The President of the Institute and several members of the Patent Committee have been more or less active in the matter, and the chairman has visited Washington once for the purpose of discussing it with friends there. Through the arguments that have been produced before the Oldfield Committee by distinguished inventors and others, and partially through the efforts of the committee, four members of which were present in Washington when the bill was discussed, the Oldfield Bill was withheld for presentation for passage at the last Congress.

It is the opinion of the committee that the efforts of the Institute should be directed towards securing the appointment of a commission, as above suggested, by the President or by Congress, for the purpose of going thoroughly into the entire patent situation, and that if such a commission

cannot be secured, the Institute should take an active part in watching and discussing such patent legislation as may be proposed for enactment by Congress.

Committee on Relations of Consulting Engineers.—The Committee on Relations of Consulting Engineers has given consideration to the question of the practicability of the adoption by the Institute of a schedule of charges for professional services analogous to the schedule of recommended charges which has been adopted by the American Institute of Consulting Engineers, but the complexity of the subject is such that the committee has not felt itself prepared to make a definite recommendation to the Board of Directors.

Constitutional Revision Committee.—The Constitutional Revision Committee was appointed last August to consider whether it would be advisable to revise the existing constitution, and if so, to recommend such changes as the committee deemed expedient and desirable. Early in December the committee issued to the membership, through THE FORUM of the PROCEEDINGS, an explanatory letter inviting comments and suggestions. A copy of this letter was mailed separately to the members of the Board of Directors, the members of all Institute committees, and the officers of the Sections and Branches. This letter resulted in the receipt of many helpful suggestions which have greatly assisted the work of the committee. It is the consensus of opinion that the existing constitution is an exceedingly strong instrument, and the changes recommended by the committee are more in the nature of a readjustment of the various sections, with minor additions and eliminations throughout, rather than a rewriting of the constitution. Certain changes have been necessary on account of inconsistencies with present practise owing to the growth and development of the Institute. As no further revision of the constitution is possible this year, the committee recommends that its report be transmitted by the Board to the succeeding administration, to be submitted to the membership next year, if deemed advisable, in accordance with the constitutional procedure.

U. S. National Committee of International Electrotechnical Commission.—No meeting of the I. E. C. has been held since the Plenary Convention in September, 1911, at Turin. Special international subcommittees have, however, held meetings during the past year; namely, the special committee on symbols; the special committee on the rating of electrical machinery; the special committee on prime movers in connection with electrical machinery. These special committees all met at Zurich in January, 1913. Mr. C. O. Mailloux attended the meetings as the representative of the U. S. National Committee. The special committee on the rating of electrical machinery also met at Paris in May, 1912, and Mr. Mailloux also attended that meeting as our representative. A statement from General Secretary C. le Maistre on the Zurich committee meetings appeared in the PROCEEDINGS of the A. I. E. E. for March, 1913, pp. 76–78.

The following official reports have been issued by the central office in London during the last year:

No. 14. List of Terms and Definitions.

No. 15. Resume of Meeting of Delegates of the Special Committee on Nomenclature held at Paris, March, 1912.

No. 16. Resume of Meeting of Delegates of the Special Committee on Symbols held at Paris, March, 1912.

No. 17. Resume of Meeting of Delegates of the Special Committee on the Rating of Electrical Machinery held at Paris, May, 1912.

No. 18. Third Annual Report to December 31, 1911.

No. 19. Resume of Meeting of Delegates of the Special Committee on Symbols held at Zurich, January, 1913.

No. 20. Resume of Meeting of Delegates of the Special Committee on the Rating of Electrical Machinery held at Zurich, January, 1913.

No. 21. Resume of Meeting of Delegates of the Special Committee on Prime Movers in connection with Electrical Plant, January, 1913.

Monthly meetings of the U. S. National Committee have been held throughout the year except during June, July and August. It has carried on a considerable amount of correspondence with the Central Office and with the Standards Committee of the A. I. E. E.

Committee on Organization of International Electrical Congress, San Francisco, 1915.—This committee was appointed last June, with a membership of over 200 Institute members, many of whom were also affiliated with other societies throughout the United States and abroad. The officers, namely the president, four vice-presidents, the secretary and the treasurer, constitute an Executive Committee of seven members, upon whom the preliminary work of organization has devolved. The Executive Committee has held frequent meetings, and tentative plans for the large features of the Congress have been discussed and in a number of respects have been decided upon. As now contemplated the Congress is to be divided into 12 sections as follows:

1. Generation, Transmission and Distribution.
2. Apparatus Design.
3. Electric Traction and Transportation.
4. Electric Power for Industrial and Domestic Use.
5. Lighting and Illumination.
6. Protective Devices; Transients.
7. Electrochemistry and Electrometallurgy.
8. Telegraphy and Telephony.
9. Electrical Instruments and Electrical Measurements.
10. Economics of Central Stations and Systems.
11. Electrophysics.
12. Miscellaneous.

The Executive Committee has under advisement at the present time questions pertaining to the further organization of the Congress, technical papers, finances, etc. Efforts are being made to co-ordinate the work of the Congress with that of the International Engineering Congress which is to meet in San Francisco two weeks later than the Electrical Congress.

John Fritz Medal.—The John Fritz Medal for 1912 was awarded to Robert Woolston Hunt, "for his contributions to the early development of the Bessemer process." The presentation was made at a special meeting of the four national engineering societies represented upon the John Fritz Medal Board of Award, on December 5, 1912, in the Engineering Societies Building, New York.

Edison Medal.—By the unanimous vote of all the members of the Edison Medal Committee, the fourth Edison Medal was awarded on

December 13, 1912, to Mr. William Stanley, of Great Barrington, Mass., "for meritorious achievement in invention and development of alternating-current systems and apparatus." The presentation will be made during the Annual Convention in June.

Board of Examiners.—The Board of Examiners has held eight meetings during the year. It has considered and referred to the Board of Directors with its recommendations a total of 1455 applications of all classes. A summary of these is as follows:

Recommended for election to the grade of Associate.....	803
Recommended for election to the grade of Member......	7
Recommended for election to the grade of Fellow.......	1
Not recommended for election to the grade of Associate.	4
Recommended for transfer to the grade of Member.....	34
Recommended for transfer to the grade of Fellow.......	11
Not recommended for transfer to the grade of Member..	2
Not recommended for transfer to the grade of Fellow....	11
Recommended for enrolment as students..............	582
Total.....................................	1455

Membership.—The net increase in membership for the year was 195. The following table shows the number of members in each grade, the total membership, and the additions and deductions which have been made during the year.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1912	5		724	6730	7459
Additions:					
Elected...........			6	746	
Transferred...........		317	443		
Reinstated...........			4	30	
Deductions:					
Died..................		1	5	24	
Resigned.............			3	134	
Dropped..............			8	416	
Transferred...........			314	446	
Membership, April 30, 1913	5	316	847	6486	7654

Net increase in membership during the year........................195

Deaths.—The following deaths have occurred during the year:

Fellow.—Horatio A. Foster.

Members.—Francis Blake, Philip Diehl, F. B. Herzog, J. A. McCrossan and F. A. Warren.

Associates.—Berthil Anderson, C. C. Badeau, A. W. Ballard, S. B. Charters, Jr., John T. Cowling, H. L. Cummings, Jr., Jos. Le Conte Davis, C. E. De Crow, M. A. Deviny, Albert J. Doty, John W. Early, Harry F. Elden, K. W. Endres, Harold Gay, John F. Hammond, James W.

Johnson, H. A. Knoener, W. P. Mifflin, Robert C. Reed, William Schulz, U. E. Taubenheim, H. C. ter Meer, Edward G. Warren and Alfred T. Ziegler.

Total deaths, 30.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

NEW YORK, May 14, 1913.

BOARD OF DIRECTORS,
American Institute of Electrical Engineers.

Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1913.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws. Haskins and Sells, chartered accountants, have audited the Institute books and their certification of the Institute finances follows.

In company with your Secretary and a member of the firm of chartered accountants, the committee has examined the securities held by the Institute and find them to be as stated in the accountants' report.

It will be noted that there is a deficit of $11,630.38 for the fiscal year. This has been caused principally by the unusual number of Institute meetings and conventions held throughout the country, and the unprecedented number of technical papers and discussions presented at these meetings, resulting in a corresponding increase in the amount of printed matter distributed to the membership in the monthly PROCEEDINGS and annual TRANSACTIONS.

The expense of printing the papers presented at the Annual Convention of June, 1912, and the Midwinter Convention held in New York in February, 1913, as well as other Institute meetings held late in the spring of 1912, has been concentrated in this fiscal year, resulting in an expenditure on account of the Meetings and Papers Committee this year of $11,650.32 more than during the preceding year, which is almost exactly the amount of the deficit.

This will tend to adjust itself during the next fiscal year, because the holding of the additional Midwinter Convention, the principal expenses of which have already been paid, will enable the Meetings and Papers Committee to reduce to some extent the publishing expenses of the coming Annual Convention.

This, together with the increase in dues for the new grade of Fellow, plus that of the large number of Associates transferred to the grade of Member, will, it is believed, result in the expenditures of the coming year being well within the income of the Institute.

Respectfully submitted,

CHARLES W. STONE,
Chairman, Finance Committee.

NEW YORK, May 12, 1913.

American Institute of Electrical Engineers,
33 West 39th Street, New York.

Dear Sirs:

Pursuant to engagement, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1913, and submit herewith our certificate and the following described exhibits:

EXHIBIT

" A "—General Balance Sheet—April 30, 1913.

" B "—Statement of Cash Receipts and Disbursements for the Year Ended April 30, 1913.

" C "—Statement of Cash Receipts and Donations for Designated Purposes. Also Disbursements, for the Year Ended April 30, 1913.

Yours truly,
(Signed) HASKINS & SELLS
Certified Public Accountants.

CERTIFICATE

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1913, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1913, that the Statements of Cash Receipts and Disbursements are correct, and that the books of the Institute are in agreement therewith.

(Signed) HASKINS & SELLS
Certified Public Accountants.

New York,
May 12, 1913.

AMERICAN INSTITUTE OF

GENERAL BALANCE SHEET

EXHIBIT A.

ASSETS.

LAND AND BUILDING:			
Interest in Engineering Societies Building, (25 to 33 West 39th Street)		$353,346.61	
One-third Cost of Land (25 to 33 West 39th Street)		180,000.00	
Total Land and Building			$533,346.61
EQUIPMENT:			
Library—Volumes and Fixtures		$33,996.36	
Works of Art, Paintings, etc		2,656.35	
Office Furniture and Fixtures		10,922.33	
Total Equipment			47,575.04
INVESTMENTS:			
Bonds:			
New York City, 4½%, 1917, Par $8,000.00.			
New York City, 4½%, 1957, Par $22,000.00		$31,952.50	
City of Wilmington, Delaware, 4½%, 1934, Par $15,000.00		15,997.50	
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $15,000.00		14,606.25	
Stock—Westinghouse Electric & Manufacturing Company, Par $50.00		50.00	
Total Investments			62,606.25
INVENTORY—BOOKS ENTITLED " TRANSACTIONS "			7,628.25
BADGES			916.80
CURRENT ASSETS:			
Cash in Bank		$2,573.09	
Secretary's Petty Cash Fund		1,250.00	
Accounts Receivable:			
Members, for Past Dues		7,175.00	
Advertisers		1,428.00	
Miscellaneous		691.54	
Interest Accrued—Investments		831.25	
Interest Accrued—Bank Balances		86.68	
Total Current Assets			14,035.56
FUNDS—(See Contra):			
Land, Building, and Endowment Fund:			
Cash	$7,115.32		
Interest Accrued	73.41		
		$7,188.73	
Life Membership Fund:			
Cash	$5,525.87		
Interest Accrued	40.00		
		5.565.87	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$472.09		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,268.00		
Interest Accrued	45.00		
		2,785.09	
Mailloux Fund:			
Cash	$77.55		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50		
		1,100.05	
General Library Fund:			
Cash	$277.95		
Interest Accrued	2.85		
		280.80	
Weaver Donation—Cash		6.69	
Total Funds			16,927.23
Total			**$683,035.74**

ELECTRICAL ENGINEERS

April 30, 1913

Liabilities.

Bond and Mortgage—United Engineering Society—One-third Interest in Land, 25 to 33 West 39th Street................		$54,000.00
Current Liabilities:		
Note Payable..	$10,000.00	
Accounts Payable—Subject to Approval by the Finance Committee..	4,335.91	
Interest Accrued on Mortgage...........................	720.00	
Interest Accrued on Note Payable.......................	131.25	
Total Current Liabilities..........................		15,187.16
Funds—(See Contra):		
Land, Building, and Endowment Fund...................	$7,188.73	
Life Membership Fund................................	5,565.87	
General Library Fund................................	280.80	
Mailloux Fund.......................................	1,100.05	
International Electrical Congress of St. Louis—Library Fund	2,785.09	
Weaver Donation.....................................	6.69	
Total Funds..................................		16,927.23
Reserve for Depreciation of Furniture and Fixtures..........		3,737.95
Surplus—Balance, May 1, 1912............................	$604,813.78	
Less Net Deficit for Year................................	11,630.38	
		593,183.40
Total,..		$683,035.74

AMERICAN INSTITUTE OF

STATEMENT OF CASH RECEIPTS AND

ENDED APRIL

EXHIBIT B.

BALANCE MAY 1, 1912:		
General Cash	$9,277.02	
Secretary's Petty Cash Fund	750.00	$10,027.02
RECEIPTS:		
Notes Payable—Loan Farmers Loan & Trust Company		$10,000.00
Entrance Fees	$3,885.00	
Current Dues	70,250.25	
Past Dues	4,653.00	
Student's Dues	4,035.00	
Advance Dues	159.00	
Transfer Fees	240.00	
Badges Sold	2,259.00	85,481.25
Sales " Transactions," etc	$1,651.03	
Subscriptions to Proceedings	2,510.80	
Advertising	10,000.26	
Binding	125.00	
Exchange	23.32	14,310.41
Italian Memorial Committee		120.00
Interest—Investments	2,626.00	
Interest—on Bank Balances	443.95	3,069.95
Total Receipts		$112,981.61
Total		$123,008.63

ELECTRICAL ENGINEERS.

DISBURSEMENTS FOR THE YEAR.

30, 1913

DISBURSEMENTS:		
Meetings and Papers Committee:		
Printing Proceedings	11,714.98	
Engravings for "	2,425.21	
Paper and cover stock for Proceedings	7,537.21	
Envelopes for Proceedings	611.37	
Binding and Mailing Proceedings	6,920.41	
Salaries	$3,957.25	
Stationery and Miscellaneous Printing	469.69	
General Expenses	68.75	
Meetings	7,906.78	
Volume No. 30 of Transactions	10,914.71	
Volume No. 31 of Transactions	960.30	
Total Disbursements Meetings and Papers Committee		$53,486.66
Executive Department:		
General Expenses	$2,335.30	
United Engineering Society—Assessments	3,375.00	
Salaries	15,583.75	
Express Charges	230.26	
Postage	3,127.32	
Badges Purchased	2,399.14	
Advertising	1,999.60	
Office Furniture and Fixtures	782.08	
Stationery and Miscellaneous Printing	3,589.46	
Year Book and Catalogue	2,841.57	
Interest on Mortgage	2,160.00	
Total Disbursements Executive Department		38,423.48
Sections Committee:		
Sections Meetings	$3,544.22	
Branch "	189.43	
Delegates to Convention—Traveling Expenses	1,763.64	
Salary and Traveling Expenses—Honorary Secretary	4,345.29	
Salaries, New York Office	2,136.00	
Stationery and Printing—New York Office	659.75	
Express Charges	6.85	
Total Disbursements Sections Committee		12,645.18
Library Committee		4,557.78
Indexing Transactions Committee		1,728.70
International Electrotechnical Commission		36.25
Annual Function		871.00
Finance Committee		150.00
Public Policy Committee		8.50
Standards Committee		7.00
Code Committee		3.50
Code of Principles of Professional Conduct Committee		6 50
Edison Medal Committee		14.25
President's Special Appropriation		424.80
Reception to Honorary Member C. E. L. Brown		106.15
Panama Convention		216.95
Italian Memorial Committee		325.25
Rearrangement of Offices		5,667.56
Special Reception to Foreign Engineers		82.34
Herbert Adams Testimonial		100.00
John Fritz Medal		262.09
E. D. Adams Special Library Fund		61.60
Total Disbursements		$119,185.54
BALANCE, APRIL 30, 1913:		
Cash in Bank	$2,573.09	
Secretary's Petty Cash Fund	1,250.00	
		$3,823.09
		$123,008.63

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES. ALSO DISBURSEMENTS, FOR THE YEAR ENDED APRIL 30, 1913

EXHIBIT C.

RECEIPTS AND DONATIONS:	
Land, Building and Endowment Fund—Donations, Interest, etc.	$1,807.79
Life Membership Fund	1,178.59
International Electrical Congress of St. Louis Library Fund Donations, and Interest	103.25
Mailloux Fund, Interest	45.00
General Library Fund, Interest	6.80
Total	$3,141.43
DISBURSEMENTS:	
Life Membership Fund	$480.00
Mailloux Fund	46.00
International Electrical Congress of St. Louis Library Fund	3.88
Total	$529.88

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1906	1907	1908	1909	1910	1911	1912	1913
Membership, April 30, each year	3870	4521	5674	6400	6681	7117	7459	7654
Receipts per Member	$12.77	$12.21	$13.01	$13.21	$13.35	$13.37	$13.19	$13.45
Disbursements per Member	10.48	11.62	11.73	10.49	12.03	11.03	12.44	15.57
Credit Balance per Member	$2.29	$.59	$1.28	$2.72	$1.32	$2.34	$.75	*$2.12

* Deficit.

The deficit indicated above was caused principally by the unusual number of meetings held during the past fiscal year, with the consequent increased expenditures for publishing the PROCEEDINGS and TRANSACTIONS, as explained in the Finance Committee's report included herein; by the expense, amounting to $5,667.56, for rearranging the Institute headquarters in order to provide better accommodations for the convenience of out-of-town members; and by an increase of over $3,000.00 in the expenditures on account of the activities of the Sections and Branches.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary*

New York, May 20, 1913.

INDEX

PAPERS AND DISCUSSIONS

INDEX OF AUTHORS

SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXXII, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

1. EDUCATION

THE NATIONAL ASSOCIATION OF CORPORATION SCHOOLS

F. C. Henderschott **Vol. xxxii—1913, pp. 1413-1416**

Purpose of organization of the National Association.

Discussion incorporated with that of paper by John Price Jackson and J. W. L Hale on "The Pennsylvania Railroad Company Apprentice Schools."

VOCATIONAL EDUCATION IN PHILADELPHIA AND VICINITY

A. J. Rowland **Vol. xxxii—1913, pp. 1417-1435**

Electrical engineering phase of vocational education—the problem and possible solutions. Descriptions of conditions and needs in Philadelphia and how they are met. Brief description of courses given in a large number of schools in and around Philadelphia.

Discussion incorporated with that of paper by John Price Jackson and J. W. L. Hale on "The Pennsylvania Railroad Company Apprentice Schools."

THE PENNSYLVANIA RAILROAD COMPANY APPRENTICE SCHOOLS

John Price Jackson and J. W. L. Hale **Vol. xxxii—1913, pp. 1437-1443**

Brief description of the organization, methods and work of the Pennsylvania Railroad School system

Discussion (including that of papers by F. C. Henderschott and A. J. Rowland) pages 1444-1455, by Messrs. Charles L. Clarke, Henry G. Stott, M. T. Crawford, J. W. L. Hale, J. Lloyd Wayne, 3rd, A. M. Buck, F. C. Caldwell, H. M. Friendly, Mr. Carron, George C. Shaad, O. J. Ferguson, Comfort A. Adams, Harry Barker and Arthur J. Rowland.

General remarks on vocational education. Experience of various teachers. Competitive education and the sorting of raw material.

2. GENERAL THEORY

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme **Vol. xxxii—1913, pp. 78-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials with respect to working temperature. General character of heat flow in electrical machinery Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on "Methods of Rating Electrical Apparatus."

NOTES ON INTERNAL HEATING OF STATOR COILS

R. B. Williamson **Vol. xxxii—1913, pp. 153-162**

Development of method of determining by calculation the maximum temperature in the stator coils for a given apparatus. Heat conductance of various commercial substances.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer Vol. xxxii—**1913, pp. 235-258**

Brief review of the quantitative relation between temperature and heat dissipation by radiation, convection and conduction and effect of room temperature, barometric pressure and moisture in each case. Experimental investigation of the effects of the last named factors in temperature tests of transformers. Recommendations for correction factors of transformer, classified by methods of cooling. Results of tests plotted as curves.

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EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

Maxwell W. Day and R. A. Beekman Vol. xxxii—**1913, pp. 259-278**

Account of special tests on various types of motors and generators in a closed room prov ded with facilities for varying and controlling the temperature of the surrounding air. Development of method of determining room temperature correction factor from observed temperature at other than standard room temperature. Temperatures in various parts of machines plotted for different methods of ventilation and room temperatures. Room temperature correction factors for various types of machines tabulated.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas Vol. xxxii—**1913, pp. 279-288**

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A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson Vol. xxxii—**1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

Discussion under Group I.

LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir Vol. xxxii—**1913, pp. 301-323**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials; also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of material. Extensive references to literature of the world on the subject of heat dissipation. Application of film theory of convection under various conditions. Results compared with older formulas.

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DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat Measurements, Rating By Heat

(a) Moving Machinery

Notes on Internal Heating of Stator Coils, By R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(b) Transformers

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(c) Temperature Correction

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(d) Cable Heating

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

Discussion pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan; H. L. Wallau, A. Herz, D. W. Roper, Edmond C. Stone, C. P. Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity and different types of cables. Temperature rise calculations.

POTENTIAL WAVES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster **Vol. xxxii—1913, pp. 749-764**

Collection of e.m.f. wave shapes to show: first, the evolution of a. c. generators; second, the effect of load and no-load shapes; third, typical waves of machinery in extensive commercial service.

Discussion under Group IV.

WAVE DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

P. M. Lincoln **Vol. xxxii—1913, pp. 765-774**

General remarks on wave distortion and criticism of Institute 10 per cent Rule. Discussion illustrated by analysis of few actual cases.

Discussion under Group IV.

A PROPOSED WAVE SHAPE STANDARD

Cassius M. Davis **Vol. xxxii—1913, pp. 775-782**

Criticism of Institute 10 per cent Rule and definite suggestions for new rules. Also description of apparatus and method of measuring the proposed distortion ratio Appendix giving derivation of distortion ratio.

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DISCUSSION GROUP IV PAPERS

pp. 731-804

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(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

the formation of corona. Results tabulated and plotted as curves. view of earlier work on corona. Application of ionization theory to co formation. Bibliography of corona and dielectric strength of air.

Discussion incorporated with that of paper by Edward Bennett on " Oscillograph Study of Corona."

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITA
W. W. Strong Vol. xxxii 1913, pp. 1755

Investigation of corona losses with uni-directional current in appar designed for the utilization of corona for precipitating dust, smoke, from fumes. Description of apparatus and tests. Results tabulated plotted as curves for both directions of the current.

Discussion incorporated with that of paper by Edward Bennett on " Oscillograph Study of Corona."

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR. III
F. W. Peek, Jr. Vol. xxxii 1913, pp. 1767

Experimental investigation and development of the laws of co formation and rupture gradient of air or gas including effects of temp ture, density, pressure above and below atmosphere, spacing, etc. T on rods and spheres. Results tabulated and plotted as curves. E tions given for calculation of gradient between rods and between sph Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper of Edward Bennett on " Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA
Edward Bennett Vol. xxxii 1913, pp. 1787

Experimental investigation of corona by means of oscillograms of charging current to a conductor producing corona. Description of met and apparatus for making the oscillograms. Oscillograms of charg current over a range of e.m.f. above and below corona e.m.f. with a tailed study and searching analysis of each curve.

Discussion, including that of papers by Messrs. J. B. Whitehead T. T. Fitch, W. W. Strong, and F. W. Peek, Jr. (pages 1810-1828, Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flow F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Benn William J. Hammer, and Harris J. Ryan.

General remarks on corona investigations and experiences. Us corona for e.m.f. measurement. Measurement of e.m.f. independent frequency. D-c. corona. Effect of frequency upon corona losses.

INSTABILITY OF ELECTRIC CIRCUITS
Charles P. Steinmetz Vol. xxxii 1913, pp. 2005-

Analysis of transient, unstable equilibrium and permanently unsta conditions in electric circuits using practical examples of each to expl the principles involved. Electrical equilibrium as affected by switchi formation of arcs, unstable loading of induction motors, hunting of s chronous machines, etc. Equations for use in determination of synch nizing and damping powers in synchronous machines.

No discussion.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer **Vol. xxxii—1913, pp. 2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering varnished cloth, hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, H. W. Fisher, M. E. Tressler, E. B. Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, H. M. Hobart, W. I. Middleton, F. M. Farmer, and J. W. Milnor.

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liquids and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

3. UNITS MEASUREMENTS AND INSTRUMENTS

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme **Vol. xxxii—1913, pp. 78-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials with respect to working temperature. General character of heat flow in electrical machinery. Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on " Methods of Rating Electrical Apparatus."

MEASUREMENT OF TEMPERATURE IN ROTATING ELECTRIC MACHINES

L. W. Chubb, E. I. Chute and O. W. A. Oetting **Vol. xxxii—1913, pp. 163-175**

Criticisms and comments on the thermometer and resistance methods of measuring temperature of electrical machinery. Description of special methods of temperature measurement including resistance exploring coils and thermocouples. Tests of temperature distribution in iron and copper of revolving field generator. Criticism of present standardization rules on temperature limits and measurements. List of recommendations for improved rules.

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METHOD OF DETERMINING TEMPERATURE OF ALTERNATING CURRENT GENERATORS AND MOTORS AND ROOM TEMPERATURE

Henry G. Reist and T. S. Eden **Vol. xxxii—1913, pp. 177-184**

Experimental investigation of thermometer design for measurement of the true temperature of electrical machinery. Comparison of results with thermometer, resistance and exploring coil methods. Correction factors for temperature of enclosed machines.

Discussion under Group I.

THERMOCOUPLES AND RESISTANCE COILS FOR THE DETERMINATION OF LOCAL TEMPERATURES IN ELECTRICAL MACHINES

J. A. Capp and L. T. Robinson **Vol. xxxii—1913, pp. 185-190**

General analysis of the methods of measuring temperature in electrical machinery giving relative merits of thermometers change of resistance

of windings, resistance thermometers, special resistance coils and thermocouples.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS AND OF COOLING MEDIUM

S. E. Johannesen and G. W. Wade Vol. xxxii—**1913**, pp. **191-211**

Analytical discussion of the various practical methods of measuring temperature with special reference to the effect of changes in the cooling conditions or room temperature. Tests showing the effect of using an idle transformer for determining the temperature lag correction factor. Recommendations for modifications of the standardization rules to cover use of idle transformer in temperature measurements.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS

W. M. McConahey and C. Fortescue Vol. xxxii—**1913**, pp. **213-236**

Conditions affecting temperature of transformers under load. Testing effectiveness of cooling or ventilation. Methods of loading transformers for temperature tests, followed by description of alternate open and short-circuit method of testing a single transformer together with mathematical proof and actual test.

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CORRECTION OF TRANSFORMER TEMPERATURES FOR VARIATION IN ROOM TEMPERATURE, TAKING INTO ACCOUNT BOTH COPPER AND IRON LOSSES

C. Fortescue Vol. xxxii—**1913**, pp. **227-234**

Development of a method of calculating the temperature rise corresponding to standard room temperature when rise of any known room temperature has been observed.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer Vol. xxxii—**1913**, pp. **235-258**

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DISCUSSION GROUP 1 PAPERS

pp. 153-357

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Notes on Internal Heating of Stator Coils, by R. B. Williamson.

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(*b*) *Transformers*

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Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb, and Phillips Thomas.

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Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fi
The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushi William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. bart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. L. L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Clark, A Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behr Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson Fortescue, John J. Frank, J. M. Wood, Carl J. Fechheimer, Paul M Gahan, H. L. Wallau, A. Hess, D. W. Roper, Edmund C. Stone, C Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of tempera measurement in connection with the rating of electrical machinery. T mal data from experience with electrical machinery, apparatus and terials. Results of extensive tests on current carrying capacity and di ent types of cables. Temperature rise calculations.

THE MYRIAWATT

H. G. Stott and Haylett O'Neill **Vol. xxxii 1913, p. 411**

Introduction of term "myriawatt" followed by conversion factor different units of energy and power and examples of the usefulness of myriawatt in practical engineering calculations.

Discussion, pages 415-421, by Messrs. H. G. Stott, C. P. Steinm Comfort A. Adams, Leo Schuler, H. M. Hobart, B. G. Lamme, Ja Burke, A. E. Kennelly, and L. W. Chubb.

Reasons for and against the adoption of myriawatt for boiler rating

INDUCTION MOTOR LOAD LOSSES

Henry G. Reist and A. E. Averrett **Vol. xxxii 1913, pp. 423-**

Discussion of the effect of load upon copper and core losses with diff ent types of slot and winding construction, followed by tests and gene conclusions as to effect of load losses.

Discussion under Group II.

STRAY LOSSES IN INDUCTION MOTORS

A. M. Dudley **Vol. xxxii 1913 pp. 429-**

Discussion of load losses of induction motors of various sizes. Reco mendations for standardisation rules covering suggested method of det mining load losses from no load tests.

Discussion under Group II.

NOTES ON INDUCTION MOTOR LOSSES

R. W. Davis **Vol. xxxii 1913, pp. 435-**

Tabulated test results of stray losses in different sizes of inducti motors.

Discussion under Group II.

LOSSES IN TRANSFORMERS

W. W. Lewis **Vol. xxxii 1913, pp. 439-**

Experimental study of the no load and load losses in different types power transformers and high tension instrument transformers showing th effect of changes in frequency, temperature, voltage and current. R

sults presented in tabular and graphic form. Recommendations for new rules defining transformer losses.

Discussion under Group II.

STRAY LOSSES IN TRANSFORMERS

C. Fortescue and W. M. McConahey **Vol. xxxii—1913, pp. 465-477**

Mathematical analysis of transformer resistance and inductance under load, no-load and short-circuit conditions. Suggested method of measuring short-circuit and impedance losses. Development of practical formulas for figuring regulation and stray losses. Recommendations for methods of obtaining losses and impedance voltage.

Discussion under Group II.

DETERMINATION OF LOAD LOSS CORRECTION FACTORS FOR ROTATING ELECTRIC MACHINES

E. M. Olin and S. L. Henderson **Vol. xxxii—1913, pp. 479-502**

Description and results of tests on d.c. and a.c. generators and synchronous converters to determine load losses and fix a correction factor that can be used with no-load measurements to get the true losses under load. Results in tabular and graphic form. Correction factors for well designed d.c. generators and motors, synchronous generators and motors, 25 and 60-cycle synchronous converters.

Discussion under Group II.

LOAD LOSSES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster and Edgar Knowlton **Vol. xxxii—1913, pp. 503-517**

Analytical discussion on load losses in a.c. generators and methods of determining them. Experimental investigation and comparison of various methods of measurement, including separation of losses, phase characteristic and circulating energy methods. Results in tabular and graphic form.

Discussion under Group II.

NOTES ON STRAY LOSSES IN SYNCHRONOUS MACHINES

F. K. Brainard **Vol. xxxii—1913, pp. 519-521**

Nature and determination of load losses in synchronous machines.

Discussion under Group II.

STRAY LOSS IN DIRECT-CURRENT COMMUTATING MACHINES

H. F. T. Erben and H. S. Page **Vol. xxxii—1913, pp. 523-529**

Description of method of testing machinery for load losses. Results of tests of number of a.c. machines given in form of loss-load curves.

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THE DETERMINATION OF STRAY LOSSES FROM INPUT-OUTPUT TESTS

L. T. Robinson **Vol. xxxii—1913, pp. 531-550**

Analysis of factors that determine the precision of input-output efficiency tests. Tabulated results of a large number of tests to determine the degree of precision possible with commercial instruments and trained observers.

Discussion under Group II.

Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.
Commutation and Brush Losses, by C. E. Wilson.

Discussion, pages 587-648, by Messrs. A. E. Averrett, B. A. Behrend, C. P. Steinmetz, James Burke, H. M. Hobart, Leo Schuler, B. G. Lamme, R. E. Hellmund, C. J. Fechheimer, Comfort A. Adams, R. B. Williamson, L. T. Robinson, M. G. Lloyd, J. M. Weed, C. Fortescue, E. A. Wagner, Charles F. Scott, J. E. Saunders, Paul M. Lincoln, W. C. Smith, G. K. Kaiser, W. B. Brady, A. H. Freeman, Alexander Gray, R. B. Treat, W. F. Dawson, F. D. Newbury, L. E. Underwood, T. M. McNiece, L. R. Berkeley and E. H. Martindale, John L. Harper, W. J. Foster, H. F. T. Erben, E. M. Olin and E. I. Chute.

Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

COMPARISON OF METHODS OF LOADING LARGE A-C. AND D-C. GENERATORS AND SYNCHRONOUS CONVERTERS FOR FACTORY TEMPERATURE TESTS

F. D. Newbury **Vol. xxxii—1913, pp. 649-665**

Classification and discussion of various methods of artificially loading rotating electrical machinery for operating temperature tests. Tests comparing various methods with actual energy load. Results tabulated.

Discussion under Group III.

COMPARISON OF METHODS OF MAKING LOAD TESTS ON A-C. GENERATORS AND ON INDUCTION MOTORS

E. F. Collins and W. E. Holcombe **Vol. xxxii—1913, pp. 667-681**

Brief description of most practical methods of obtaining mormal load temperature in a.c. generators and induction motors under no-load and partial load conditions. Comparisons of results with actual full load tests. Results in tabular form.

Discussion under Group III.

NOTES ON METHODS OF MAKING LOAD TESTS ON LARGE INDUCTION MOTOR

A. M. Dudley **Vol. xxxii—1913, pp. 683-690**

Brief description and discussion of loading back and artificial loading tests for induction motors. Comparison of series of tests by circulating current method with actual load test. Results tabulated

Discussion under Group III.

LOAD TEST ON TRANSFORMERS

J. J. K. Madden **Vol. xxxii—1913, pp. 691-702**

Brief description of various loading back tests on two or more transformers of different types. Description of method of testing single transformer for running temperature with artificial loading Results of tests tabulated and method of test recommended to Standards Committee.

Discussion under Group III.

THE EXPERIMENTAL DETERMINATION OF THE REGULATION OF ALTERNATORS

A B. Field **Vol. xxxii—1913, pp. 783-787**

Criticisms of present Standardization Rules for specification and determination of regulation, followed by definite recommendations.

Discussion under Group IV.

REGULATION OF DEFINITE POLE ALTERNATORS

Soren H. Mortensen **Vol. xxxii—1913, pp. 789-794**

Description of method of determining regulation by Potier's triangle. Comparison of this method with Institute Rules method and with actual tests on a large number of three-phase, two-phase and single-phase machines. Results tabulated and saturation curves plotted for each method.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Swi'ches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sanford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY

C. L. Fortescue and S. W. Farnsworth **Vol. xxxii—1913, pp. 893-906**

Development and method of designing solid insulation between two bodies so that the natural air field will not be altered; that is, so that the

max mum dielectric strength of the air along the surface of the insulator can be utilized. Description of apparatus for measuring and plotting equal potential curves in the electric field.

Discussion incorporated with that of paper by C. Fortescue on "The Application of a Theorem of Electrostatics to Insulation Problems."

TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND

A. E. Kennelly and F. W. Lieberknecht Vol. xxxii—**1913, pp. 1283-1303**

Detailed description and a series of tests on a very long artificial telephone line. E.m.f. and current being measured both as to phase and amplitude. Results tabulated and plotted as vector diagrams. Bibliography of articles of measurement on artificial telephone lines and allied topics.

Discussion incorporated with that of paper of Messrs. H. M. Friendly and A. E. Burns on "Automatic Methods in Long Distance Telephone Operation."

AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION

H. M. Friendly and A. E. Burns Vol. xxxii—**1913, pp. 1305-1332**

Description of equipment and operation of long distance automatic system of the Northwestern Long Distance Telephone Company.

Discussion (including that of paper by Messrs. A. E. Kennelly and F. W. Lieberknecht), pages 1333-1344, by Messrs. F. K. Vreeland, E. H. Colpitts, D. C. Jackson, George A. Campbell, R. S. Brown, J. B. Taylor, H. M. Friendly and Oberlin Smith.

Telephone line calculations. Definitions of iterative impedance and propagation constants. Use of integraph in solving equations.

ELECTROLYTIC CORROSION OF IRON IN SOILS

Burton McCollum and K. H. Logan Vol. xxxii—**1913, pp. 1345-1403**

Experimental investigation of electrolysis of iron in soil from various cities taking up each variable factor separately and determining its influence upon corrosion. Effect of current density, moisture, temperature, depth of burial, oxygen, kind of iron, chemicals in soil, etc. upon corrosion efficiency. Experimental study of earth resistance and the factors that affect it. Detailed description of tests and tabulation of results.

Discussion, pages 1404-1412, by Messrs. J. L. R. Hayden, Alexander Maxwell, D. C. Jackson, Hugh T. Wreaks, Harold V. Bozell, Harry Barker, F. C. Caldwell, J. C. Lincoln, Henry G. Stott, Albert F. Ganz and Burton McCollum.

General remarks on electrolysis from street railway currents and its prevention.

OPERATION OF FREQUENCY CHANGERS

N. E. Funk Vol. xxxii—**1913, pp. 1713-1730**

General review of theory of parallel operation of synchronous frequency changers. Detailed description of method of synchronizing with rotating synchroscope and a special synchronizing indicator. Examples of use of indicator.

Discussion (including that of papers by H. R. Summerhayes and B. G. Jamieson) pages 1731-1736, by Messrs. D. B. Rushmore, F. D. Newbury, F. C. Caldwell, Paul M.Lincoln, H. M. Hobart, Henry W. Peck, S. D.

Sprong, H. R. Summerhayes, J. C. Lincoln, D. W. Roper and N. E. Funk.

General remarks on the advisability of running machinery unattended. Oil pressure for facilitating the starting of large machines.

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. Vol. xxxii—**1913**, pp. **1767-1785**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure above and below atmospheric, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett Vol. xxxii—**1913**, pp. **1787-1809**

Experimental investigation of corona by means of oscillograms of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong and F.W. Peek, Jr.,) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett, William J. Hammer and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer Vol. xxxii—**1913**, pp. **2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering varnished cloth, hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, H. W. Fisher, M. E. Tressler, E. B. Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, H. M. Hobart, W. I. Middleton, F. M. Farmer, and J. W. Milnor.

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liquids and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

4. INSULATION AND DIELECTRIC PHENOMENA

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme Vol. xxxii—**1913**, pp. **78-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials

with respect to working temperature. General character of heat flow in electrical machinery. Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on "Methods of Rating Electrical Apparatus."

METHODS OF RATING ELECTRICAL APPARATUS

W. L. Merrill, W. H. Powell and Charles Robbins **Vol. xxxii—1913, pp. 91-100**

Recommendations for the standardization of electrical apparatus ratings according to a plan that will more truly represent the capability of the apparatus than the present rules. Ratings for different classes of service. Temperature limitation of different classes of insulation and different kinds of service. Recommendations for name plate stamping.

Discussion (including that of paper by Messrs. C. P. Steinmetz and B. G. Lamme), pages 101-152, by Messrs. F. B. Crocker, James Burke, Henry G. Stott, W. L. Waters, H. U. Hart, B. A. Behrend, James M. Smith, Schuyler Skaats Wheeler, P. Torchio, M. G. Lloyd, Charles P. Steinmetz, Henry G. Reist, B. G. Lamme, Alexander Gray, R. F. Schuchardt, C. E. Skinner, C. J. Fechheimer, W. L. Merrill, W. H. Powell, Charles F. Scott, Comfort A. Adams, C. L. de Muralt, H. M. Hobart, A. E. Kennelly, A. M. Rossman, C. E. Allen, E. A. Wagner, G. I. Stadeker, J. W. Welsh, Edmund C. Stone and William F. Dawson.

Comments and criticisms of the recommendations for standard methods of rating and limiting temperatures of electrical apparatus. Experience in the operation of electrical machinery with regard to safe operating temperature. American standardization rules compared with European standards. International Electro-technical Commission rules compared with Inst tute rules. Defense and explanation of the proposed new standardization rules.

THE SPHERE SPARK GAP

S. W. Farnsworth and C. L. Fortescue **Vol. xxxii—1913, pp. 733-737**

Criticisms of needle gap and recommendation of sphere gap to Standards Committee.

Discussion under Group IV.

THE CALIBRATION OF THE SPHERE GAP VOLTMETER

L. W. Chubb and C. Fortescue **Vol. xxxii—1913, pp. 739-748**

Description of results and method of calibration tests upon sphere gaps. Results plotted and tabulated for three different sizes of spheres.

Discussion under Group IV

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY

C. L. Fortescue and S. W. Farnsworth **Vol. xxxii—1913, pp. 893-906**

Development and method of designing solid insulation between two bodies so that the natural air field will not be altered; that is, so that the maximum dielectric strength of the air along the surface of the insulator can be utilized. Description of apparatus for measuring and plotting equal potential curves in the electric field

Discussion incorporated with that of paper by C. Fortescue on "The Application of a Theorem of Electrostatics to Insulation Problems".

THE APPLICATION OF A THEOREM OF ELECTRO-STATICS TO INSULATION PROBLEMS

C. Fortescue — **Vol. xxxii—1913, pp. 907-925**

Mathematical analysis of electric field about a sphere and various other geometric shapes. Application of flux distribution theory to design of core and shell-type transformer insulation. Diagrammatic illustrations of transformer insulation construction. Pin and suspension type line insulators designed upon same principles. 1,000,000-volt transformer.

Discussion (including that of paper by Messrs. C. L. Fortescue and S. W. Farnsworth), pages 926-951, by Messrs. Percy H. Thomas, Ralph D. Mershon, C. O. Mailloux, F. W. Peek, Jr., A. E. Kennelly, Philip Torchio, J. Murray Weed, Harris J. Ryan and C. Fortescue.

General remarks on insulation design and the dielectric current. Sharp criticism and hearty praise of author's papers. Effect of lightning stroke and high frequency upon insulator design. Limitations of condenser type terminals. Effect of frequency, external bodies, surface conduction upon insulation design.

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE SUSPENSION INSULATORS

F. W. Peek, Jr. — **Vol. xxxii—1913, pp. 1457-1461**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS

J. A. Sandford, Jr. — **Vol. xxxii—1913, pp. 1462-1470**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

INSULATOR TESTING SPECIFICATION FOR INSULATORS HAVING AN OPERATING VOLTAGE EXCEEDING 25,000 VOLTS

Percy H. Thomas — **Vol. xxxii—1913, pp. 1471-1479**

Discussion (including that of papers by Messrs. F. W. Peek, Jr., and J. A. Sanford, Jr.) pages 1480-1508, by Messrs. F. W. Peek, Jr., J. A. Sanford, Jr., P. H. Thomas, L. C. Nicholson, H. W. Crozier, H. Koganei, M. T. Crawford, C. O. Mailloux, Paul M. Lincoln, Hugh T. Wreaks, E. E. F. Creighton, Ralph D. Mershon, E. M. Hewlett, P. W. Sothman and C. F. Scott.

Criticisms and suggestions for specifications for the design and testing of insulators. Effect of simultaneous mechanical and electrical stresses, tests.

THE ELECTRIC STRENGTH OF AIR—IV

J. B. Whitehead and T. T. Fitch — **Vol. xxxii—1913, pp. 1737-1753**

Description of tests and apparatus and discussion of results of a series of investigations on the effects of pressure, temperature and density upon the formation of corona. Results tabulated and plotted as curves. Review of earlier work on corona. Application of ionization theory to corona formation. Bibliography of corona and dielectric strength of air.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona.'

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION

W. W. Strong Vol. xxxii, **1913**, pp. **1755-1765**

Investigation of corona [illegible] apparatus designed for the [illegible] of [illegible] precipitating [illegible], etc. from fumes. Description of apparatus and tests. Results tabulated and plotted as curves [illegible].

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. Vol. xxxii, **1913**, pp. **1767-1786**

Experimental investigation and development of the laws of corona formation and rupture gradient of air [illegible] effect of temperature, density, pressure, above and below atmospheric [illegible]. Tests on rods and spheres. Results tabulated and plotted [illegible]. Equations given for calculation of [illegible] between spheres. Rupture explained [illegible].

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett Vol. xxxii, **1913**, pp. **1787-1809**

Experimental investigation of corona by means of oscillograms of the charging current [illegible]. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of [illegible] above and below [illegible] with a detailed study and searching analysis of each [illegible].

Discussion, including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong, and F. W. Peek, Jr., pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, [illegible], F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, [illegible], Edward Bennett, William J. Hammer, and Harris J. Ryan.

General remarks on corona investigations and [illegible]. Use of corona for [illegible] measurement. Measurement of [illegible] independent of frequency. [illegible] corona. Effect of frequency upon corona loss.

THE GULF OF GEORGIA SUBMARINE TELEPHONE CABLE

E. P. LaBelle and L. P. Crim Vol. xxxii, **1913**, pp. **1877-1889**

Specifications for submarine cable [illegible] Krarup system. Method of laying, splicing, locating faults, etc. Krarup [illegible] system compared with the Pupin coil system of loading.

No discussion.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer Vol. xxxii, **1913**, pp. **2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering [illegible], hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, [illegible], Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, [illegible], W. I. Middleton, F. M. Farmer and J. W. [illegible].

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liqu ds and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

5. ELECTRIC CONDUCTORS

CURRENT RATING OF ELECTRIC CABLES

Ralph W. Atkinson and H. W. Fisher **Vol. xxxii—1913, pp. 325-331**

Brief analytical discussion of heating of cables showing the relative importance of various factors that influence either the heating or the cooling. Formulas and tables for calculating the load capacity of various types and sizes of cables. Example of calculation.

Discussion under Group I.

THE HEATING OF CABLES CARRYING CURRENT

Saul Dushman **Vol. xxxii—1913, pp. 333-357**

Detailed description of current-carrying capacity and heating test upon certain cables together with results in tabular and graphic form. Discussion of the results developing from general application. Thermal properties of various cable insulating materials.

Discussion under Group I.

DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat Measurements, Rating by Heat

(*a*) *Moving Machinery*

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperatures of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank, and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure, and Humidity on The Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.
Laws of Heat Transmission in Electrical Machinery by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.
The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity and different types of cables. Temperature rise calculations.

8. TRANSFORMERS

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS AND OF COOLING MEDIUM

S. E. Johannesen and G. W. Wade **Vol. xxxii—1913, pp. 191-211**

Analytical discussion of the various practical methods of measuring temperature with special reference to the effect of changes in the cooling conditions of room temperature. Tests showing the effect of using an idle transformer for determining the temperature lag correction factor. Recommendations for modification of the standardization rules to cover use of idle transformer in temperature measurements.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS

W. M. McConahey and C. Fortescue **Vol. xxxii—1913, pp. 213-236**

Conditions affecting temperature of transformers under load. Testing effectiveness of cooling or ventilation. Methods of loading transformers for temperature tests, followed by description of alternate open and short-circuit method of testing a single transformer together with mathematical proof and actual tests.

Discussion under Group I.

CORRECTION OF TRANSFORMER TEMPERATURES FOR VARIATION IN ROOM TEMPERATURE, TAKING INTO ACCOUNT BOTH COPPER AND IRON LOSSES

C. Fortescue **Vol. xxxii—1913, pp. 227-234**

Development of a method of calculating the temperature rise corresponding to standard room temperature when rise of any known room temperature has been observed.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer **Vol. xxxii—1913, pp. 235-258**

Brief review of the quantitative relation between temperature and heat dissipation by radiation, convection and conduction and effect of room temperature, barometric pressure and moisture in each case. Experimental investigation of the effects of the last named factors in temperature tests of transformers. Recommendations for correction factors of transformer, classified by methods of cooling. Results of tests plotted as curves.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

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A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson **Vol. xxxii—1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

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LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir **Vol. xxxii—1913, pp. 301-323**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials; also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of materials. Extensive references to literature of the world on the subject of heat dissipation. Application of film theory of convection under various conditions. Results compared with older formulas.

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DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat, Measurements Rating by Heat

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Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Funct on of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

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General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity of different types of cables Temperature rise calculations.

LOSSES IN TRANSFORMERS

W. W. Lewis **Vol. xxxii—1913, pp. 439-462**

Experimental study of the no-load and load losses in different types of power transformers and high-tension instrument transformers showing the effect of changes in frequency, temperature, voltage and current. Results presented in tabular and graphic form. Recommendations for new rules defining transformer losses.

Discussion under Group II.

STRAY LOSSES IN TRANSFORMERS

C. Fortescue and W. M. McConahey **Vol. xxxii—1913, pp. 465-477**

Mathematical analysis of transformer resistance and inductance under load, no-load and short-circuit conditions. Suggested method of measuring short-circuit and impedance losses. Development of practical

formulas for figuring regulation and stray losses. Recommendations for methods of obtaining losses and impedance voltage.

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(*a*) *Induction Motors*

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Stray Losses in Induction Motors, by A. M. Dudley.
Notes on Induction Motor Losses, by R. W. Davis.

(*b*) *Transformers*

Losses in Transformers, by W. W. Lewis.
Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(*c*) *Generators, A-C and D-C.*

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.
Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.
Notes on Stray Losses in Synchronous Machines, by F. K Brainard.
Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page.

(*d*) *Error of Tests*

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson
Sources of Error in the Efficiency Determination of Rotating Electric Machines by Elmer I. Chute, and William Bradshaw.

(*e*) *Brush Losses*

Brush Friction and Contact Losses by H. F. T. Erben and A. H. Freeman.
Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.
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Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

LOAD TESTS ON TRANSFORMERS

J. J. K. Madden **Vol. xxxii—1913, pp. 691-702**

Brief description of various loading back tests on two or more transformers of different types. Description of method of testing single transformer for running temperature with artificial loading. Results of tests tabulated and method of test recommended to Standards Committee.

Discussion under Group III.

SOURCES OF ERROR IN TRANSFORMER TESTS

W. M. McConahey and C. Fortescue **Vol. xxxii—1913, pp. 703-708**

Brief outl ne of various commercial tests of power transformers, pointing out possible errors and how to avo'd them.

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DISCUSSION GROUP III PAPERS

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Method of Testing Apparatus for Performance

(*a*) *Generators and Induction Motors*

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests on A-C. Generators and on Induction Motors, by E. F. Col ins and W. E. Holcombe.

Notes on Method of Making Load Tests on Large Induct on Motors, by A M. Dudley.

(*b*) *Transformers*

Load Test on Transformers, by J. J. K. Madden.

Source of Error in Transformer Tests by W M. McConahey and C. Fortescue

Discussion, pages 711-729, by Messrs. A E Averrett, R. B Williamson, R. E. Hellmund, B. G. Lamme, Leo Schuler, E.I. Chute, Pau M. Lincoln, F. D Newbury, A J. Porskievies, Alexander Gray B. A. Behrend, H. M. Hobart, Stuart L. Henderson J. J. K. Madden, Charles P. Steinmetz, W J Foster, Edgar Knowlton, C. J. Fechheimer J. M Weed and M. G. Lloyd

General remarks and opinions on methods of loading generators, motors, and transformers artificially, based largely on experience. Suggested definition for transformer ratio.

WAVE DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

P. M. Lincoln **Vol. xxxii—1913, pp. 765-774**

General remarks on wave distortion and criticism of Inst tute 10 per cent Rule. Discussion illustrated by analysis of few actua' cases.

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A PROPOSED WAVE SHAPE STANDARD

Cassius M. Davis **Vol. xxxii—1913, pp. 775-782**

Criticism of Institute 10 per cent Rule and definite suggestions for new rules. Also description of apparatus and method of measuring the proposed distortion ratio. Appendix giving derivation of distortion ratio.

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DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*d*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

THE APPLICATION OF A THEOREM OF ELECTRO-STATICS TO INSULATION PROBLEMS

C. Fortescue **Vol. xxxii—1913, pp. 907-925**

Mathematical analysis of electric field about a sphere and various other geometric shapes. Application of flux distribution theory to design of core and shell-type transformer insulation. Diagrammatic illustrations of transformer insulation construction. Pin and suspension type line insulators designed upon same principles. 1,000,000-volt transformer.

Discussion (including that of paper by Messrs. C. L. Fortescue and S. W. Farnsworth), pages 926-951, by Messrs. Percy H. Thomas, Ralph D. Mershon, C. O. Mailloux, F. W. Peek, Jr., A. E. Kennelly, Philip Torchio, J. Murray Weed, Harris J. Ryan and C. Fortescue.

General remarks on insulation design and the dielectric circuit. Sharp criticism and hearty praise of author's papers. Effect of lightning stroke and high frequency upon insulator design. Limitations of condenser type terminals. Effect of frequency, external bodies, surface conduction upon insulation design.

9. ELECTRICAL MACHINERY AND APPARATUS

HIGH SPEED TURBO-ALTERNATORS—DESIGNS AND LIMITATIONS

B. G. Lamme **Vol. xxxii—1913, pp. 1-37**

Analytical discussion of developments and present status of turbo-alternator design, covering general mechanical construction, vibration, temperature rise and distribution, insulation losses, regulation and all other important factors that enter into the problem. The paper is especially complete as to ventilation, temperature and insulation.

Discussion, pages 38-78, by Messrs. Henry G. Reist, R. B. Williamson, Philip Torchio, C. J. Fechheimer, William LeRoy Emmet, Paul M. Lincoln, Peter Junkersfeld, H. M. Hobart, W. L. Waters, Comfort A. Adams, Allan B. Field, W. J. Foster, K. E. Czeija, Alexander Gray, Bradley T. McCormick, Jens Bache-Wiig, F. H. Clough and B. G. Lamme.

General remarks on turbo-alternator design. Some difficulties encountered in operation. Equation for maximum output. Much data and experience on ventilation and insulation of turbo-alternators. Analysis of heat flow and temperature distribution.

METHODS OF RATING ELECTRICAL APPARATUS

W. L. Merrill, W. H. Powell and Charles Robbins **Vol. xxxii—1913, pp. 91-100**

Recommendations for the standardization of electrical apparatus ratings according to a plan that will more truly represent the capability of the apparatus than the present rules. Ratings for different classes of service. Temperature limitation of different classes of insulation and different kinds of service. Recommendations for name plate stamping.

Discussion (including that of paper by Messrs. C. P. Steinmetz and B. G. Lamme), pages 101-152, by Messrs. F. B. Crocker, James Burke, Henry G. Stott, W. L. Waters, H. U. Hart, B. A. Behrend, James M. Smith, Schuyler Skaats Wheeler, P. Torchio, M. G. Lloyd, Charles P. Steinmetz, Henry G. Reist, B. G. Lamme, Alexander Gray, R. F. Schuchardt, C. E. Skinner, C. J. Fechheimer, W. L. Merrill, W. H. Powell, Charles F. Scott, Comfort A. Adams, C. L. de Muralt, H. M. Hobart, A. E. Kennelly, A. M. Rossman, C. E. Allen, E. A. Wagner, G. I. Stadeker, J. W. Welsh, Edmund C. Stone and William F. Dawson.

Comments and criticisms of the recommendations for standard methods of rating and limiting temperatures of electrical apparatus. Experience in the operation of electrical machinery with regard to safe operating temperature. American standardization rules compared with European standards. International Electro-technical Commission rules compared with Institute rules. Defence and explanation of the proposed new standardization rules.

NOTES ON INTERNAL HEATING OF STATOR COILS

R. B. Williamson **Vol. xxxii—1913, pp. 153-162**

Development of method of determining by calculation the maximum temperature in the stator coils for a given apparatus. Heat conductance of various commercial substances.

Discussion under Group I.

MEASUREMENT OF TEMPERATURE IN ROTATING ELECTRIC MACHINES

L. W. Chubb, E. I. Chute and O. W. A. Oetting **Vol. xxxii—1913, pp. 163-175**

Criticisms and comments on the thermometer and resistance methods of measuring temperature of electrical machinery. Description of special methods of temperature measurement including resistance exploring coils and thermocouples. Tests of temperature distribution in iron and copper of revolving field generator. Criticism of present standardization rules on temperature limits and measurements. List of recommendations for improved rules.

Discussion under Group I.

METHOD OF DETERMINING TEMPERATURE OF ALTERNATING CURRENT GENERATORS AND MOTORS AND ROOM TEMPERATURE

Henry G. Reist and T. S. Eden **Vol. xxxii—1913, pp. 177-184**

Experimental investigation of thermometer design for measurement of the true temperature of electrical machinery. Comparison of results with thermometer, resistance and exploring coil methods. Correction factors for temperature of enclosed machines.

Discussion under Group I.

THERMOCOUPLES AND RESISTANCE COILS FOR THE DETERMINATION OF LOCAL TEMPERATURES IN ELECTRICAL MACHINES

J. A. Capp and L. T. Robinson **Vol. xxxii—1913, pp. 185-190**

General analysis of the methods of measuring temperature in electrical machinery giving relative merits of thermometers, change of resistance of windings, resistance thermometers, special resistance coils and thermocouples.

Discussion under Group I.

EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

Maxwell W. Day and R. A. Beekman **Vol. xxxii—1913, pp. 259-278**

Account of special tests on various types of motors and generators in a closed room provided with facilities for varying and controlling the temperature of the surrounding air. Development of method of determining room temperature correction factor from observed temperature at other than standard room temperature. Temperatures in various parts of machines plotted for different methods of ventilation and room temperatures. Room temperatures correction factors for various types of machines tabulated.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

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A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson Vol. xxxii—**1913**, **pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

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LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir Vol. xxxii—**1913**, **pp. 301-323**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials, also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of materials. Extensive references to literature of the world on the subject of heat dissipation: Application of film theory of convection under various conditions. Results compared with older formulas.

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Heating, Heat Measurements, Rating by Heat

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Measurement of Temperature of Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

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Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

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Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer.

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Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity of different types of cables. Temperature rise calculations.

INDUCTION MOTOR LOAD LOSSES

Henry G. Reist and A. E. Averrett — Vol. xxxii—1913, pp. 423-428

Discussion of the effect of load upon copper and core losses with different types of slot and winding construction, followed by tests and general conclusions as to effect of load losses.

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STRAY LOSSES IN INDUCTION MOTORS

A. M. Dudley — Vol. xxxii—1913, pp. 429-434

Discussion of load losses of induction motors of various sizes. Recommendations for standardization rules covering suggested method of determining load losses from no-load tests.

Discussion under Group II.

NOTES ON INDUCTION MOTOR LOSSES

R. W Davis — Vol. xxxii—1913, pp. 435-437

Tabulated test results of stray losses in different sizes of induction motors.

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DETERMINATION OF LOAD LOSS CORRECTION FACTORS FOR ROTATING ELECTRIC MACHINES

E. M. Olin and S. L. Henderson — Vol. xxxii—1913, pp. 479-502

Description and results of tests on d.c. and a.c. generators and synchronous converters to determine load losses and fix a correction factor that can be used with no-load measurements to get the true losses under load. Results in tabular and graphic form. Correction factors for well designed d.c. generators and motors, synchronous generators and motors, 25 and 60-cycle synchronous converters.

Discussion under Group II.

LOAD LOSSES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster and Edgar Knowlton — Vol. xxxii—1913, pp. 503-517

Analytical discussion on load losses in a.c. generators and methods of determining them. Experimental investigation and comparison of various methods of measurement, including separation of losses, phase characteristic and circulating energy methods. Results in tabular and graphic form.

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(*b*) *Transformers*

Losses in Transformers, by W. W. Lewis.

Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(*c*) *Generators, A-C and D-C.*

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.

Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.

Notes on Stray Losses in Synchronous Machines, by F. K. Brainard.

Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page.

(*d*) *Errors of Tests*

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson.

Sources of Error in the Efficiency Determination of Rotating Electric Machines, by Elmer I. Chute and William Bradshaw.

(*e*) *Brush Losses*

Brush Friction and Contact Losses, by H. F. T. Erben and A. H. Freeman.

Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.

Commutation and Brush Losses, by C. E. Wilson.

Discussion, pages 587-646, by Messrs. A. E. Averrett, B. A. Behrend, C. P. Stenimetz, James Burke, H. M. Hobart, Leo Schuler, B. G. Lamme, R. E. Hellmund, C. J. Fechheimer, Comfort A. Adams, R. B. Williamson, L. T. Robinson, M. G. Lloyd, J. M. Weed, C. Fortescue, E. A. Wagner, Charles F. Scott, J. E. Saunders, Paul M. Lincoln, W. C. Smith, G. K. Kaiser, W. B. Brady, A. H. Freeman, Alexander Gray, R. B. Treat, W. F. Dawson, F. D. Newbury, L. E. Underwood, T. M. McNiece, L. R. Berkeley and E. H. Martindale, John L. Harper, W. J. Foster, H. F. T. Erben, E. M. Olin and E. I. Chute.

Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

COMPARISON OF METHODS OF LOADING LARGE A-C. AND D-C. GENERATORS AND SYNCHRONOUS CONVERTERS FOR FACTORY TEMPERATURE TESTS

F D. Newbury **Vol. xxxii—1913, pp. 649-665**

Classification and discussion of various methods of artificially loading rotating electrical machinery for operating temperature tests. Tests comparing various methods with actual energy load. Results tabulated.

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COMPARISON OF METHODS OF MAKING LOAD TESTS ON A-C. GENERATORS AND ON INDUCTION MOTORS

E. F. Collins and W. E. Holcombe **Vol. xxxii—1913, pp. 667-681**

Brief description of most practical methods of obtaining normal load temperature in a.c. generators and induction motors under no-load and partial load conditions. Comparisons of results with actual full load tests. Results in tabular form.

Discussion under Group III.

NOTES ON METHODS OF MAKING LOAD TESTS ON LARGE INDUCTION MOTORS
A. M. Dudley **Vol. xxxii—1913, pp. 683-690**

Brief description and discussion of loading back and artificial loading tests for induction motors. Comparison of series of tests by circulating current method with actual load test. Results tabulated.

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pp. 649-708

Method of Testing Apparatus for Performance

(*a*) *Generators and Induction Motors*

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests in A-C. Generators and on Induction Motors, by E. F. Collins and W. E. Holcombe.

Notes on Method of Making Load Tests on Large Induction Motors, by A. M. Dudley.

(*b*) *Transformers*

Load Tests on Transformers, by J. J. K. Madden.

Sources of Error in Transformer Tests, by W. M. McConahey and C. Fortescue.

Discussion, pages 711-729, by Messrs. A. E. Averrett, R. B. Williamson, R. E. Hellmund, B. G. Lamme, Leo Schuler, E. I. Chute, Paul M. Lincoln, F. D. Newbury, A. J. Porskievies, Alexander Gray, B. A. Behrend, H. M. Hobart, Stuart L. Henderson, J. J. K. Madden, Charles P. Steinmetz, W. J. Foster, Edgar Knowlton, C. J. Fechheimer, J. M. Weed and M. G. Lloyd.

General remarks and opinions on methods of loading generators, motors, and transformers artificially, based largely on experience. Suggested definition for transformer ratio.

POTENTIAL WAVES OF ALTERNATING-CURRENT GENERATORS
W. J. Foster **Vol. xxxii—1913, pp. 749-764**

Collection of e.m.f. wave shapes to show: first, the evolution of a.c. generators, second, the effect of load and no-load shapes; third, typical waves of machinery in extensive commercial service.

Discussion under Group IV.

THE EXPERIMENTAL DETERMINATION OF THE REGULATION OF ALTERNATORS
A. B. Field **Vol. xxxii—1913, pp. 783-78**

Criticisms of present Standardization Rules for specification and determination of regulation, followed by definite recommendations.

Discussion under Group IV.

REGULATION OF DEFINITE POLE ALTERNATORS
Soren H. Mortensen **Vol. xxxii—1913, pp. 789-794**

Description of method of determining regulation by Potier's triangle. Comparison of this method with Institute Rules method and with actual tests on a large number of three-phase, two-phase and single-phase machines. Results tabulated and saturation curves plotted for each method.

Discussion under Group IV.

GENERATOR AND PRIME MOVER CAPACITIES

David B. Rushmore and Eric A. Lof Vol. xxxii—1913, pp. **795-804**

Brief review of relation between rating of steam and gas prime movers and generators to which they are connected. Discussion of selection of water wheel capacity with due regard for hydraulic as well as electrical load conditions. Efficiency curves of different types of prime movers.

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DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr,, C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters. George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave form measurement, test data. Calculation of alternator regulation and description of method.

OPERATION OF TRANSMISSION LINES

Lee Hagood Vol. xxxii—1913, pp. **855-881**

Control of voltage and power factor in medium and high-tension transmission lines by means of synchronous machines. Examples showing methods of calculating the performance of the system and demonstrating the savings and improved service resulting from use of synchronous machines. Performance curves given for each transmission system discussed.

Discussion, pages 882-[illegible] [illegible] Hagood, Robert [illegible] [illegible] L. N. Peart, [illegible]

General [illegible] line regulation. [illegible] operation.

ALTERNATING CURRENT MOTORS FOR THE ECONOMIC OPERATION OF MINE FANS

F. B. Crosby Vol. xxxii 1913, pp. 1073-1086

Brief review of [illegible] with special reference to regulating [illegible] Efficiency curves for different methods.

Discussion, pages 1087-1096, by Messrs. [illegible] Wilfred Sykes, George R. Wood, [illegible] W. O. E. Schumann, [illegible]

General remarks [illegible] regulator commutating machines [illegible]

THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING

F. D. Newbury Vol. xxxii 1913, pp. 1509-1526

Analytical [illegible] of the starting performance of synchronous motors, started [illegible] Reasoning substantiated by actual tests [illegible] plotted as curves for different conditions.

Discussion incorporated with that of paper by [illegible] on "Electrical Requirements of Certain Machines in the Rubber Industry."

COMMUTATING POLE SATURATION IN D. C. MACHINES

Harold F. Stokes Vol. xxxii 1913, pp. 1527-1543

Adaptation of [illegible] method of obtaining saturation in transformers to commutating poles under load [illegible] and method of test and calculation.

Discussion incorporated with that of paper by [illegible] on "Electrical Requirements of Certain Machines in the Rubber Industry."

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

[illegible]ohn C. Parker Vol. xxxii 1913, pp. 1559-1564

Suitable uses for [illegible] pumps and air compressors for favorable starting [illegible]

Discussion incorporated with that of paper by [illegible] on "Electrical Requirements of Certain Machines in the Rubber Industry."

OPERATION OF FREQUENCY CHANGERS

N. E. Funk Vol. xxxii 1913, pp. 1713-1730

General review of theory of parallel operation of [illegible] frequency changers. Detailed description of method of [illegible] with rotating synchroscope and a special [illegible] Examples of use of indicator.

Discussion, including that of papers by [illegible] and B. G. Jamieson pages 1701-1712, by Messrs. [illegible] F. D. Newbury, F. C. Caldwell, Paul M. [illegible] Henry W. Peck, S. D. Sprong, [illegible] and N. E. Funk.

General remarks on the [illegible] Oil pressure for facilitating the starting of large machines.

INSTABILITY OF ELECTRIC CIRCUITS

Charles P. Steinmetz Vol. xxxii—1913, pp. 2005-2021

Analysis of transient, unstable equilibrium and permanently unstable conditions in electric circuits using practical examples of each to explain the principles involved. Electrical equilibrium as affected by switching, formation of arcs, unstable loading of induction motors, hunting of synchronous machines, etc. Equations for use in determination of synchronizing and damping powers in synchronous machines.

No discussion.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

Alfred E. Waller Vol. xxxii—1913, pp. 2023-2035

Consideration of some of the most important factors in the design of lighting equipment for motor cars. Brief description of different mechanical and electrical methods of controlling the output of the generator. More detailed description of a certain system using a shunt generator with a Tirrill regulator method of control.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

Alexander Churchward Vol. xxxii—1913, pp. 2037-2041

Advantages of constant-speed generator for battery charging and series motor for starting. Performance curves for battery charging and lighting under various conditions of car speed and battery charge for constant-speed generator. Also performance curves for variable-speed generators.

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ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

Frank Conrad Vol. xxxii—1913, pp. 2043-2051

Description of constant-current generator system for ignition, lighting and starting. Description of ignition device, designed to vary angular time of contact with speed. Oscillograms of ignition current and curves of 4 and 6-cylinder motor torque.

Discussion (including that of papers by Alfred E. Waller and Alexander Churchward), pages 2052-2075, by Messrs. H. Ward Leonard, Leonard Kebler, Amon W. Copley, A. D. T. Libby, Harold Goodwin, Jr., C. E. Wilson, Benjamin F. Bailey, Kingston Forbes, Alexander Churchward, Alfred E. Waller, Frank Conrad, Alden L. McMurtry, Frederick S. Dellenbaugh, Jr., and John R. King.

Relative merits of constant-speed and variable-speed generators for motor car operation. Tests of efficiency of slipping clutch and bucking series coil. Relative advantages of various car wiring systems. Rosenberg dynamo for variable speed lighting.

10. PRIME MOVERS AND STEAM BOILERS

GENERATOR AND PRIME MOVER CAPACITIES

David B. Rushmore and Eric A. Lof Vol. xxxii—1913, pp. 795-804

Brief review of relation between rating of steam and gas prime movers and generators to which they are connected. Discussion of selection

of water wheel capacity with due regard for hydraulic as well as electrical load conditions. Efficiency curves of different types of prime movers.

Discussion under Group IV.

STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS

H. G. Stott and W. S. Gorsuch **Vol. xxxii—1913, pp. 1619-1651**

Detailed analysis of cost of energy production with a view of classifying items for intelligent comparison of one plant with another. Method of allowing for differences in wages, coal cost and load factor. Suggested forms for tabulating costs and depreciation.

Discussion, pages 1652-1683, by Messrs. Henry Floy, Carl Schwartz, William McClellan, C. O. Mailloux, Peter Junkersfeld, D. B. Rushmore, L. P. Crecelius, W. G. Carlton, August H. Kruesi, D. C. Jackson, Ralph D. Mershon, P. W. Sothman, H. M. Hobart, W. S. Gorsuch, E. D. Dreyfus, Charles S. Ruffner, and S. D. Sprong.

General remarks on methods of figuring costs and depreciation. Classification of accounts used by certain large corporations and societies. Methods of comparing costs of production in different plants.

POWER FROM MERCURY VAPOR

W. L. R. Emmet **Vol. xxxii—1913, pp. 2133-2149**

Exposition of a process of utilizing mercury vapor pressure in a turbine and then absorbing the exhaust heat in a steam boiler which serves as a condenser, the steam being used in the usual way. Theory of process and account of experimental investigation together with description of the mercury boiler construction.

No discussion.

11. CENTRAL STATIONS

PURCHASED POWER IN COAL MINES

H. C. Eddy **Vol. xxxii—1913, pp. 1029-1034**

Brief analysis of the advantages of central station supply over isolated plant.

Discussion incorporated with that of paper by C. W. Beers on "Central Station Power for Coal Mines."

CENTRAL STATION POWER FOR COAL MINES

C. W. Beers **Vol. xxxii—1913, pp. 1035-1045**

Advantages of central station supply from the coal miner's point of view. Analysis of fixed charges and operating costs for isolated mine power plant. Outline of power contract between central station company and coal mining company.

Discussion (including that of paper by H. C. Eddy), pages 1046-1053, by Messrs. K. A. Pauly, George H. Morse, E. D. Dreyfus, T. E. Tynes, W. Partridge, W. E. D ckinson, H. C. Eddy, George R. Wood and C. W. Beers.

General remarks on the purchase of central station energy for coal mines. Load factors and cost.

CENTRAL STATION POWER FOR MINES

J. S. Jenks Vol. xxxii—1913, pp. 1097-1102

Brief outline of development of supply of electric energy for mines by the West Penn system, describing the equipment, troubles encountered and how they were overcome.

Discussion incorporated with that of paper by Messrs. H. M. Warren and A. S. Biesecker on "Characteristics of Substation Loads at the Anthracite Collieries of the Lackawanna R. R. Co."

CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R. R. CO.

H. M. Warren and A. S. Biesecker Vol. xxxii—1913, pp. 1103-1109

Description of tests with results on 15 mine substations. Load curves and load factors.

Discussion (including that of paper by J. S. Jenks) pages 1110-1119, by Messrs. Graham Bright, W. A. Thomas, J. Paul Clayton, George R. Wood, H. M. Warren, George H. Morse, C. W. PenDell, P. M. Lincoln, Sidney G. Vigo, C. I. Weaver, and T. E. Tynes.

General remarks on rates and methods of charging for central station energy. Definition of load factor and effect on rates.

MINING LOADS FOR CENTRAL STATIONS

Wilfred Sykes and Graham Bright Vol. xxxii—1913, pp. 1121-1136

Classification of mining service and analytical discussion of power requirements and load characteristics of each type of service. Outline and discussion of various methods of charging for and measuring central station service. Suggestions for contracts.

Discussion, pages 1137-1147, by Messrs. P. M. Lincoln, Sidney G. Vigo, Theodore Swann, H. C. Eddy, and Graham Bright.

General remarks on methods of charging for central station service with illustrations from actual practice of large companies.

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

John C. Parker Vol. xxxii—1913, pp. 1559-1564

Suitable uses for synchronous motors. Special adaptation of pumps and air compressors for favorable starting conditions.

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General remarks on methods of figuring costs and depreciation. Classification of accounts used by certain large corporations and societies. Methods of comparing costs of production in different plants.

RELATION OF PLANT SIZE TO POWER COST

P. M. Lincoln Vol. xxxii—1913, pp. 1981-1992

Superficial analysis of economic advantages of electric energy production in a central plant as compared with generation of energy for the same purposes in a number of small isolated plants, regarded from the standpoint of first cost, operating economy and load characteristics.

Discussion, pages 1993-2004, by Messrs. Harry Archer Hornor, W. C. L. Eglin, P. V. Stevens, C. O. Mailloux, M. G. Lloyd, J. P. Jackson, G. J. Blum and P. M. Lincoln.

Cases where isolated plant has marked advantage over central station supply.

FACTORS DETERMINING A REASONABLE CHARGE FOR PUBLIC UTILITY SERVICE

M. E. Cooley Vol. xxxii—1913, pp. 2077-2095

Clear exposition of the various elements that enter into the financing, organization, operation and insurance of a public service corporation or utility, tracing the steps taken and expenses incurred from its inception to its completion.

No discussion.

12. PARALLEL OPERATION

OPERATION OF FREQUENCY CHANGERS

N. E. Funk Vol. xxxii—1913, pp. 1713-1730

General review of theory of parallel operation of synchronous frequency changers. Detailed description of method of synchronizing with rotating synchroscope and a special synchronizing indicator. Examples of use of indicator.

Discussion (including that of papers by H. R. Summerhayes and B. G. Jamieson) pages 1731-1736, by Messrs. D. B. Rushmore, F. D. Newbury, F. C. Caldwell, Paul M. Lincoln, H. M. Hobart, Henry W. Peck, S. D. Sprong, H. R. Summerhayes, J. C. Lincoln, D. W. Roper and N. E. Funk.

General remarks on the advisability of running machinery unattended. Oil pressure for facilitating the starting of large machines.

13. TRANSMISSION LINES

OPERATION OF TRANSMISSION LINES

Lee Hagood Vol. xxxii—1913, pp. 855-881

Control of voltage and power factor in medium and high-tension transmission lines by means of synchronous machines. Examples showing methods of calculating the performance of the system and demonstrating the savings and improved results resulting from use of synchronous machines. Performance curves given for each transmission system discussed.

Discussion, pages 882-892, by Messrs. Herbert W. Crozier, Lee Hagood, Robert Sibley, Professor Cory, L. P. Jorgensen, J. P. Jollyman, L. N. Peart, J. P. Francis, R. C. Powell, and H. Y. Hall.

General remarks on use of synchronous machines for transmission line regulation. Actual experience and tests from systems of operation.

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1767-1785**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure above and below atmosphere, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett **Vol. xxxii—1913, pp. 1787-1809**

Experimental investigation of corona by means of oscillographs of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong, and F. W. Peek, Jr.) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett, William J. Hammer, and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

EFFECTS OF ICE LOADING ON TRANSMISSION LINES

V. H. Greisser **Vol. xxxii—1913, pp. 1829-1844**

Account of actual experience with ice coatings and experimental investigation with artificial loads similar in magnitude and distribution to those observed in actual service on a suspension insulator line of the Washington Water Power Company, Spokane. Sags and rises plotted as curves for different loadings. Suggested construction to prevent damage and short-circuits.

No discussion.

15. DISTRIBUTION SYSTEMS

CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R. R. CO.

H. M. Warren and A. S. Biesecker **Vol. xxxii—1913, pp. 1103-1109**

Description of tests with results on 15 mine substations. Load curves and load factors.

Discussion (including that of paper by J. S. Jenks) pages 1110-1119, by Messrs. Graham Bright, W. A. Thomas, J. Paul Clayton, George R. Wood, H. M. Warren, George H. Morse, C. W. PenDell, P. M. Lincoln, Sidney G. Vigo, C. I. Weaver, and T. E. Tynes.

General remarks on rates and methods of charging for central station energy. Definition of load factor and effect on rates.

Discussion, pages 1903-1912, by Messrs. W. V. Hunt, Frederick D. Nims, W. Fraser, C. F. Terrell, L. G. Robinson, J. A. Lighthipe, A. A. Miller, R. W. Pope, R. F. Hayward, V. Karapetoff and John B. Fisken.

General remarks on construction, equipment and operation of portable and automatic substations.

INDUSTRIAL SUBSTATIONS

H. P. Liversidge **Vol. xxxii—1913, pp. 1955-1974**

Outline of development of the substation as a part of the distribution system. Brief description of a series of industrial substations with circuit diagrams and layouts, dwelling upon the important characteristics of design and general construction.

Discussion, pages 1975-1979, by Messrs. W. C. L. Eglin, P. M. Lincoln, John Mathews, G. W. Brooks, P. V. Stephens, Charles Penrose, Harold Goodwin, Jr., and H. P. Liversidge.

General comments upon substation design.

16. CONTROL, REGULATION AND SWITCHING

RATING OF OIL CIRCUIT BREAKERS WITH REFERENCE TO RUPTURING CAPACITY

George A. Burnham **Vol. xxxii—1913, pp. 731-732**

Suggestions for Standard Committee.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

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General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

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General remarks on use of synchronous machines for transmission line regulation. Actual experience and test from systems of operation.

SAFEGUARDING THE USE OF ELECTRICITY IN MINES

H. H. Clark **Vol. xxxii—1913, pp. 1055-1062**

Analysis of accidents caused by electricity and the factors that determine the risk. Directions for reducing and preventing such accidents. Effect of electrical operation in reducing the usual run of accidents in mines.

Discussion, pages 1063-1071, by Messrs. C. A. Lauffer, J. S. Jenks, Ralph D. Mershon, George R. Wood, Graham Bright, W. E. Dickinson, Wilfred Sykes, L. R. Palmer and Harold H. Clark.

General remarks on electrical accidents in mines. Directions for resuscitation by the Schafer prone pressure method. Statistics on mine accidents.

CONSTANT-VOLTAGE TRANSMISSION

H. B. Dwight **Vol. xxxii—1913, pp. 1545-1588**

Comparison of transmission line operation with voltage regulated at the generator and with voltage regulated at both generator and receiver. Analytical discussion of advantages and disadvantages of synchronous condensers and numerical examples of savings in 100-mile and 200-mile transmission lines. Results plotted as curves.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

AUTOMATIC SUBSTATIONS

H. R. Summerhayes **Vol. xxxii—1913, pp. 1685-1698**

Brief review of well-known applications of remote control of electrical apparatus and machinery. Description of remote controlled synchronous converter substation of Detroit Edison Company—installation, operation and protection.

Discussion incorporated with that of paper by N. E. Funk on "Operation of Frequency Changers."

A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT

John B. Fisken Vol. xxxii—1913, pp. 1891-1902

Description of construction and equipment of a portable or "take-down" substation for mountainous districts. Description of water relay for transformer protection. Cost of construction and operation.

Discussion, pages 1903-1912, by Messrs. W. V. Hunt, Frederick D. Nims, W. Fraser, C. F. Terrill, L. G. Robinson, J. A. Lighthipe, A. A. Miller, R. W. Pope, R. F. Hayward, V. Karapetoff and John B. Fisken.

General remarks on construction, equipment and operation of portable and automatic substations.

17. TRACTION

2400-VOLT RAILWAY ELECTRIFICATION

H. M. Hobart Vol. xxxii—1913, pp. 1159-1188

Comparison of the cost of operation of high-tension electric systems with steam. Numerical examples worked out in detail for various classes of railroad service and results discussed. Methods of calculation given and results tabulated.

Discussion incorporated with that of paper by Charles P. Kahler on "Trunk Line Electrification."

TRUNK LINE ELECTRIFICATION

Charles P. Kahler Vol. xxxii—1913, pp. 1189-1226

Detailed and comprehensive analysis of the economics of railroad electrification with well digested data from actual practice. Example of heavy electrification worked out and all items tabulated for easy reference and results derived which determine the actual return on the investment. Everything taken into consideration. Effect of substitution of electric motive power for steam upon railroad operation. Comparative cost of operation by steam and electricity.

Discussion (including that of paper by H. M. Hobart), pages 1227-1260, by Messrs. A. H. Armstrong, F. E. Wynne, George Hill, W. S. Murray, A. H. Babcock, H. Y. Hall and G. W. Welsh, F. W. Carter, F. C. Merriell, H. F. Parshall, Charles P. Kahler, Roger T. Smith and H. M. Hobart.

General remarks on the economics of railroad electrification. D-c. vs. a-c. electrification. Possibilities of mercury rectifiers in railroad work. Comparison of steam and electric locomotives for a given service. Cost of distribution system and steam and electric locomotives. Cost data and other assumptions used for comparing steam with electricity given in full.

ELECTROLYTIC CORROSION OF IRON IN SOILS

Burton McCollum and K. H. Logan Vol. xxxii—1913, pp. 1345-1403

Experimental investigation of electrolysis of iron in soil from various cities taking up each variable factor separately and determining its influence upon corrosion. Effect of current density, moisture, temperature, depth of burial, oxygen, kind of iron, chemicals in soil, etc. upon corrosion efficiency. Experimental study of earth resistance and the factors that affect it. Detailed description of tests and tabulation of results.

Discussion, pages 1404-1412, by Messrs. J. L. R. Hayden, Alexander Maxwell, D. C. Jackson, Hugh T. Wreaks, Harold V. Bozell, Harry

Barker, F. C. Caldwell, J. C. Lincoln, Henry G. Stott, Albert F. Ganz, and Burton McCollum.

General remarks on electrolysis from street railway currents and its prevention.

MOUNTAIN RAILWAY ELECTRIFICATION

Allen H. Babcock **Vol. xxxii—1913, pp. 1845-1875**

Detailed description of a report on the problem of electrification going very thoroughly into the question of construction and operation costs for the electric system and the corresponding cost for steam. Assumptions and methods of estimates fully given. Complete cost figures in tabular form. Study of economical spacing of substations with results plotted as curves.

No discussion.

18. LIGHTING AND LAMPS

TUNGSTEN LAMPS OF HIGH EFFICIENCY

Irving Langmuir **Vol. xxxii—1913, pp. 1913-1933**

Experimental investigation of the causes of blackening. Detailed analysis of the various elements of the lamp as sources of gas and description of the effect of the various gases upon the performance of the lamp. Development of preventative measures.

Discussion incorporated with that of paper by Messrs. Irving Langmuir and J. A. Orange on " Tungsten Lamps of High Efficiency."

TUNGSTEN LAMPS OF HIGH EFFICIENCY

Irving Langmuir and J. A. Orange **Vol. xxxii—1913, pp. 1935-1946**

Description of design, construction and performance of nitrogen-filled lamps.

Discussion (including that of paper by Irving Langmuir) pages 1947-1954, by Messrs. John B. Taylor, John W. Howell, Farley Osgood, J. E. Randall, William McClellan, Irving Langmuir, John W. Lieb, Jr., M. G. Lloyd, and H. M. Fales.

Blackening of lamps. Advantages of nitrogen lamp in projection lantern work. Relative economy of incandescent lamps on basis of filament temperature.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

Alfred E. Waller **Vol. xxxii—1913, pp. 2023-2035**

Consideration of some of the most important factors in the design of lighting equipment for motor cars. Brief description of different mechanical and electrical methods of controlling the output of the generator. More detailed description of a certain system using a shunt generator with a Tirrill regulator method of control.

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Frank Conrad **Vol. xxxii—1913, pp. 2043-2051**

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